PASSIVE COOLING BY UTILIZING THE COMBINED PCM / ALUMINUM FOAM MATRIX TO IMPROVE SOLAR PANELS PERFORMANCE: INDOOR INVESTIGATION

Abdulmunem R. Abdulmunem
Electromechanical Engineering Department, University of Technology/Baghdad. Iraq
E-mail:abdulmunemraad@yahoo.com

ABSTRACT

In this study, utilizing the PCM latent heat of fusion to absorbing the heat energy from photovoltaic panels was done. This method works as a passive cooling to regulate the PV panel's temperature in hot climate regions. To enhance the important effective physical properties such as thermal conductivities (k_{eff}) for this material, aluminum foam matrix was used with paraffin wax. This led to good temperature distribution inside PCM and more heat absorption from PV panel. The experimental results indicated that the PV panel temperature drooped from (61.39 ^{o}C) to (46.2 ^{o}C) by using PCM only, and to (39.58^{o}C) by using PCM/Aluminum foam matrix at the test end, (i.e. the percentage drooping of PV panel temperature was (25.03%) by using PCM only, and it was (35.51%) by using PCM/Aluminum foam matrix). This droop in temperature enhances the electrical performance of PV panel such as maximum power generated, fill factor (FF), etc. The improving in electrical efficiency of PV panel at the test end was from (10.19%) to (12.37%) with using PCM only, and to about (13%) with using PCM/Aluminum foam matrix.

Keywords: Phase change materials; PCM; Aluminum foam matrix; PV panel; passive cooling.

التبريد السلبي من خلال الاستفادة من مدمج PCM / مصفوفة الالمنيوم الرغوي لتحسين اداء الالواح الشمسية : تحقيق مختبري

عبد المنعم رعد عبد المنعم

الخلاصة :

في هذه الدراسة، تم استثمار الحرارة الكامنة للانصهار للمواد المتغيرة الطور PCM لامتصاص الطاقة الحرارية من الالواح الكهروضوئية ، هذه الطريقة تعمل كطريقة تبريد سلبي لتنظيم درجة حرارة الالواح الكهروضوئية في المناطق ذات المناخ الحار. لتحسين الخصائص الفيزيائية الفعالة المهمة كالموصلية الحرارية (k_{eff}) لهذه المادة، تم استخدام مصفوفة الالمنيوم الرغوي مع شمع البارافين، ادى هذا الى توزيع درجات حرارة جيد داخل المادة المتفيرة الطور PCM والى زيادة في امتصاص الحرارة من اللوح الكهروضوئي. بينت النتائج العملية ان درجة حرارة اللوح الكهروضوئي انخفضت من(61.39 ^{o}C) الى (46.2 ^{o}C) باستخدام المادة المتغيرة الطور PCM فقط، وانها انخفضت الى (39.58^{o}C) باستخدام المادة المتغيرة الطور مع مصفوفة الالمنيوم الرغوي في نهاية الفحص،(بمعنى اخر، النسبة المئوية لانخفاض درجة حرارة اللوح الكهروضوئي كانت (25.03%) باستخدام ال PCM فقط، وكانت (35.51%) باستخدام المادة المتغيرة الطور مع مصفوفة الالمنيوم الرغوي). هذا الانخفاض بدرجات الحرارة ادى الى تحسين بالاداء الكهربائي للوح الكهروضوئي كاعلى قدرة كهربائية متولدة، عامل الاملاء(FF) ، الخ. التحسين بالكفائة الكهربائية في نهاية الفحص كانت من (10.19%) الى (12.37%) باستخدام ال PCM فقط، والى حوالى (13%) باستخدام المادة المتغيرة الطور مع مصفوفة الالمنيوم الرغوي.

كلمات مفتاحية: مواد متغيرة الطور; PCM ; مصفوفة الالمنيوم الرغوي; لوح كهروضوئي; تبريد سلبي .

Received : 2017 - 3 - 23
Accepted : 2017- 5 - 18

NOMENCLATURE:

A_{PV} =PV panel area (m^2).
C_p = specific heat (kJ/kg.K).
C_{peff} = Effective specific heat (kJ/kg.K).
C_{pf} =specific heat of liquid phase (kJ/kg.K).
C_{ps} =specific heat of solid phase (kJ/kg.K).
e = dimensionless factor (0.339).
FF= Fill factor.
G= Irradiation (W/m^2).
Impp= PV current at maximum power point (A).
I_{SC}= PV short circuit current (A).
k =thermal conductivity (W/ m.K).
k_{eff} = effective thermal conductivity of the composite system.
k_f =thermal conductivity of fluid phase (W/ m.K).
k_s= thermal conductivity of solid phase (W/ m.K).
PCM=Phase change material.
P_{max}= Maximum power (W).
T =Temperature (°C).
Vmpp= PV voltage at maximum power point (V).
V_{OS}= PV open circuit voltage (V).
ρ =Density (kg/m^3).
ρ_{eff}= Effective density (kg/m^3).
ρ_f= Density of liquid phase (kg/m^3).
ρ_s= Density of solid phase (kg/m^3).
η_e = PV electrical efficiency (%).
ω = porosity of the metal foam .

INTRODUCTION

A photovoltaic panel is more affected by the temperature. The rising temperature of the silicone cells that made of these PV panels led to drooping in the electrical power generated. The rising in the PV panel temperature comes from two ways, the first: internally by operating the silicon cells to generate electricity, the second: externally by rising the ambient temperature. Thus the PV panels are less efficient in hot climate such as Iraq country. For this reason the need arise to regulate the PV panel's temperature. One of the most important methods for regulation temperature of PV panels is the passive cooling (no need to power) by using latent heat of fusion of phase change materials (PCM) to absorb heat of the silicon cells. The PCMs can be divided in to two categories depending on the melting point, (Inorganic) high melting point PCM above (200 ^oC) that using in power plants, and (Organic) low melting point PCM below (200 ^oC) that used in buildings and heat recovery systems. The organic PCM gives desirable properties at low temperature applications, such as limited super cooling with no phase segregation and non-corrosion. But the low thermal conductivity is presented for both types of PCM **(Zalba et al. [2003], Py et al. [2001])**.

There are many research carried out to improving the thermal response of PCM by using various high thermal conductivity materials. The methods abbreviate by dispersing high thermal conductivity fibers or particles into PCM. **Tong et al. [1995]** studied the water freezing by insert a continuously connected of aluminum foam matrix into water as phase change material. The result shows that when insert the aluminum foam matrix into water gives a very important way for enhancing the water freezing. **Bauer et al. [2000]** improved a structure thermal energy storage combined plate consist of aluminum foam core filled with Phase change material. A high efficient device to store energy which consists of cooper foam matrix and water was made by **Chi et al. [2011]**. Due to the using of copper foam matrix, the process of cold charging energy storage devices was more faster. **Jinghua et al. [2012]** used aluminum foam matrix impregnated with stearic acid and paraffin to prepared shape-stabilized PCMs. The thermal property of the stabilized shape PCM was investigated. The PCMs fill fraction was more than 80% and the latent value of the aluminum foam/ PCM and aluminum foam/ stearic acid composite are (72.8 kJ/kg) and (66.6 kJ/kg) respectively. **Cui [2012]** prepared a composite of copper foam matrix filled with paraffin as phase change material, the results indicated that the copper matrix is not only gives more uniform temperature distribution within the PCM, it also led to reduce the time of charge. **Sheng et al. [2013]** studied the heat transfer performance of prepared composite of copper foam matrix with hydrate/metal foam combined phase change material by using the barium hydroxide octahydrate ($Ba(OH)2\cdot 8H2O$) as PCM. The result showed that copper foam matrix with high porosity is not only lead to improving in the heat transfer rate of $Ba(OH)2\cdot 8H2O$, it also reduced the super cooling of the PCM effectively. **Maria C. [2016]** gives the experimental module for using the PCM in hybrid PV/T/PCM system, the experimental results shows that the PCM is the most effective means to remove heat from the PV module . Based on literature, this work aimed to investigate experimentally the enhancing in PV panel performance by utilizing the PCM latent heat of fusion to absorb the heat energy. Paraffin wax is used as passive cooling material integrated with aluminum foam matrix to enhance the important effective physical properties of this material .

METHODOLOGY

Effective physical properties composite PCM/ Aluminum foam matrix

To calculate the effective thermal conductivity of the composite PCM/ Aluminum foam matrix, **Boomsma [2001]** developed the next relations:

$$k_{eff} = \frac{\sqrt{2}}{2(X_A+X_B+X_C+X_D)} \quad (1)$$

Where:

$$X_A = \frac{4L}{\left(2e^2+\pi L(1-e)\right)k_s + \left(4-2e^2-\pi L(1-e)\right)k_f} \quad (2)$$

$$X_B = \frac{(e-2L)^2}{(e-2L)e^2k_s + \left(2e-4L-(e-2L)e^2\right)k_f} \quad (3)$$

$$X_C = \frac{\left(\sqrt{2}-2e\right)^2}{2\pi L^2\left(1-2e\sqrt{2}\right)k_s + 2\left(\sqrt{2}-2e-\pi L^2\left(1-2e\sqrt{2}\right)\right)k_f} \quad (4)$$

$$X_D = \frac{2e}{e^2k_s+(4-e^2)k_f} \quad (5)$$

And:

$$L = \sqrt{\frac{\sqrt{2}(2-\left(\frac{5}{8}\right)e^{3}\sqrt{2}-2\omega}{\pi(3-4e\sqrt{2}-e)}} \quad ,e=0.339 \tag{6}$$

The effective density and specific heat can be calculated by **N.Tsolas [2012]:**

$$\rho_{eff} = \omega * \rho_f + (1-\omega) * \rho_s \tag{7}$$

$$C_{Peff} = \omega * C_{Pf} + (1-\omega) C_{Ps} \tag{8}$$

Electrical performance of PV panel

The definition of FF (filling factor) is the maximum ratio of the power production from the solar cell to the multiplication product of V_{OC} and I_{SC}, where V_{OC} is the maximum solar cell available voltage at the solar cell current equal to zero, and I_{SC} is the current produced from the solar cell at the voltage through the solar cell equal to zero **C. H. Cox et al. [1985]** i.e.:

$$FF = \frac{P_{max}}{I_{sc} * V_{oc}} \tag{9}$$

Where:

$$P_{max} = I_{mpp} * V_{mpp} \tag{10}$$

Then the electrical efficiency of PV panel (η_e) is :-

$$\eta_e = \frac{P_{max}}{G * A_{PV}} \tag{11}$$

EXPERIMENTAL PART

System configuration

The commercial PV panels consist of individual small size panels, these panels connected in parallel and series to produce large size panels with different power and sizes as the amount of voltage and current in line with market need. In this study the system was constructed to understand the behavior of these individual PV panels with rising temperature carefully, and to show the influence of using composite PCM/Aluminum Foam Matrix as passive cooling material on PV power generation .

The model test consists of (13.5cm x 13.5cm) polycrystalline silicon cells PV panel with maximum power (1.6 Watt) at standard conditions (Irradiation= 1000W/m^2, Temperature= 25 ^oC). This panel is coupled in the back side with internal dimensions (13cm length x 13cm width x 4cm depth) aluminum container and (0.7mm) plate thickness. In the first case, the container is filled with paraffin wax as PCM to show the effect of using this material as PV panel passive cooling. The paraffin wax specifications are shown in table (1). To enhance the

PCM performance as cooling material, the aluminum foam matrix with (ω =96.1%, k=237 W/m.K, Cp= 0.902 kJ/kg.K) was used with paraffin wax in the second case as shown in figure (1). The tests are done indoor to show the changes under constant irradiance and to eliminate the changes in the environment such as wind speed, etc. A (500 W) halogen solar lamp was used to simulate the solar radiation. The solar lamp was set at distance (40cm) to give irradiation (800 W/m^2).

Experimental Measurements

The tests are done at the university of technology / electromechanical department/renewable energy lab. Three K-type thermocouples with accuracy (±0.4%) are puts at depth (1cm, 2cm and 3cm) for each test case. To give average PV panel temperature, the fourth and fifth thermocouples are placed in front and rear PV panel surface as shown in figure (2). These thermocouples are connected to digital thermo recorder type (TM-946) with accuracy (±0.02%). Light intensity is measured with an (Protek / DM-301) sensor with accuracy (±0.7%). The electrical measurements of PV panel are taken by digital electrical measurement board type (Dellrenzo DL9021) with accuracy (±0.2%). Figure (3) shows the complete system with the schematic diagram .

DISCUSSION OF THE RESULTS

Table (2) show the changes in the physical properties of the passive cooling material used in this study depending on equations (1, 7 and 8). The increasing in the effective thermal conductivity from (0.2 W/m.k) for paraffin wax to (2.257563) for composite PCM/Aluminum foam matrix led to good absorbing of heat energy from PV panel comparative with paraffin wax as shown in figure (4). The PV panel temperature drooped from (61.39 ^{o}C) without using any material to (46.2 ^{o}C) by using PCM only, and it drooped to (39.58^{o}C) by using PCM/Aluminum foam matrix at the test end. The duration of each test case was (35 min) and at constant irradiation (G=800W/m^2) .

Figure (5) shows that the drop in PV panel temperature with composite PCM/Aluminum foam matrix is (35.51%), and it is (25.03%) with PCM only comparison with PV panel without any material. It seen from thermocouples reading the use of aluminum foam matrix with PCM led to good temperature distribution in side PCM(the curves more close) comparative with PCM only as shown in figure (6) and figure (7).

Figure (8) and figure (9) show the enhancing in the both Impp and Vmpp for each test case with time as drooping in PV panel temperature, and this led to increasing in maximum power generated depending on equation (10) as shown in figure (10).

Figures (11) and (12) show the changes in Isc and Voc with time respectively as the temperature drops. It is seen that no more changes in Isc values comparative with Impp in figure (8). The changes are in Voc values depending on the changes in PV panel temperature comparative with Vmpp in figure (9). This changes in Voc is due to effect on fill factor (FF) values depending on equation (9) as shown in figure (13). The enhancing in FF is from (0.705) without using any material to (0.802) with using PCM only, and it is (0.812) with using PCM/Aluminum foam matrix.

Figure (14) shows the improvement in electrical efficiency of PV panel from (10.19%) without using any material to (12.37%) with using PCM only, and it is about (13%) with using PCM/Aluminum foam matrix. The percentages of increasing PV panel electrical performance comparison with PV panel without PCM are shown in figure (15) .

CONCLUSIONS

The main important conclusions from this study can be summarized:

1. The increase in PV panel's temperature led to a decrease in electrical power generation from these panels.
2. It is possible to use the latent heat of fusion for paraffin wax (PCM) to absorb the heat energy from photovoltaic panels. This method works as a passive cooling to regulate the PV panels temperature in hot climate regions.
3. The low thermal conductivity of paraffin wax present and playing important role, the using of Aluminum foam matrix in side PCM led to enhancing in the important effective physical properties such as thermal conductivities (k_{eff}), and this led to good temperature distribution inside PCM and more heat absorption from PV panel .

Table (1) :- Paraffin wax specifications

Parameters	**Values**
Density [kg/m^3]	880 (Solid)/760 (Liquid)
Thermal conductivity [W/m K]	0.2
Specific heat [kJ/kg K]	2.9 (Solid)/2.2 (Liquid)
Latent heat [kJ/kg]	142
Melting temperature [^{o}C]	42

Table (2): Results of effective physical specification of composite PCM/ aluminum foam matrix

Material	**K (W/m.k)**	**ρ(kg/m3)**	**Cp(kJ/kg.K)**
Aluminum	237	2700	0.902
Paraffin wax	0.2	880	2.900
Effective specification	2.257563	950.98	2.822078

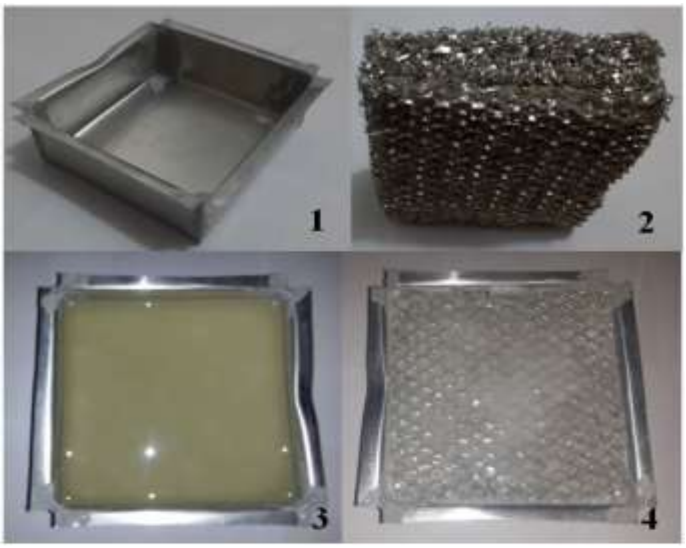


Fig (1) 1-aluminum container, 2-aluminum foam matrix, 3- aluminum container with PCM, 4-aluminum container with composite PCM/ aluminum foam matrix .

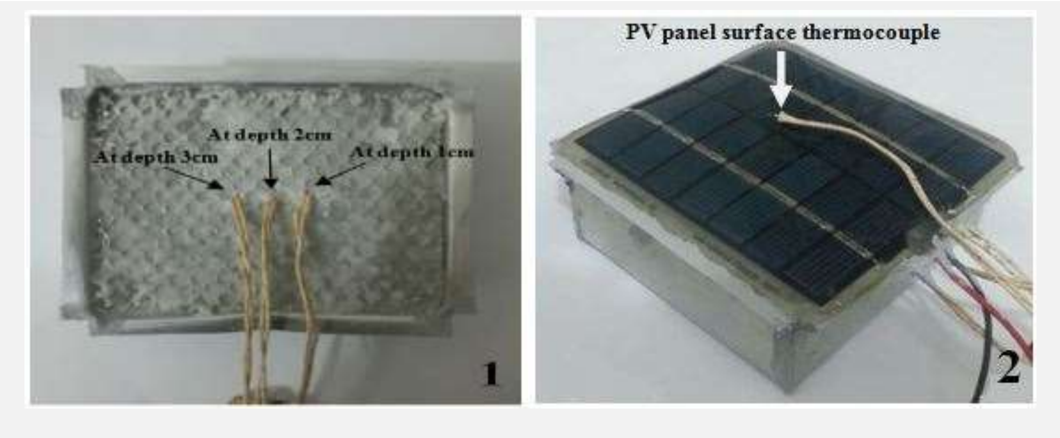
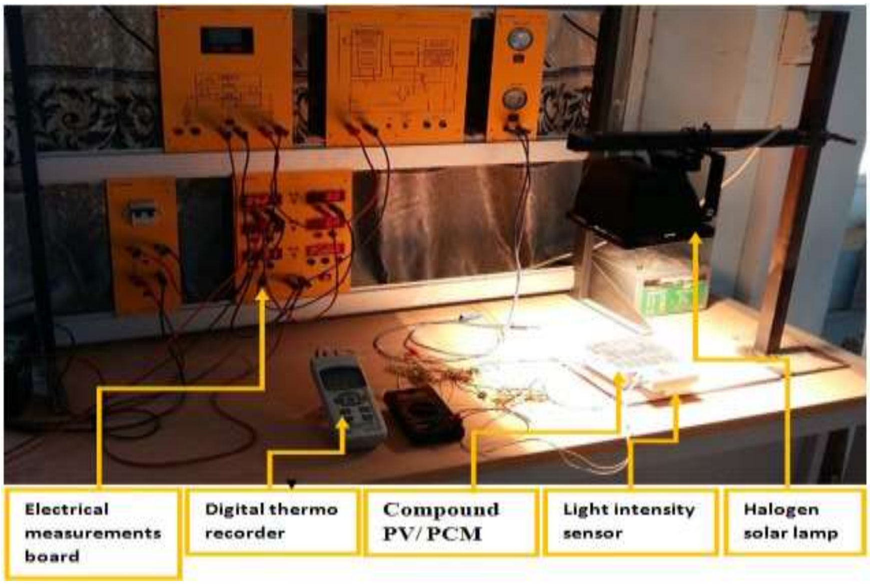
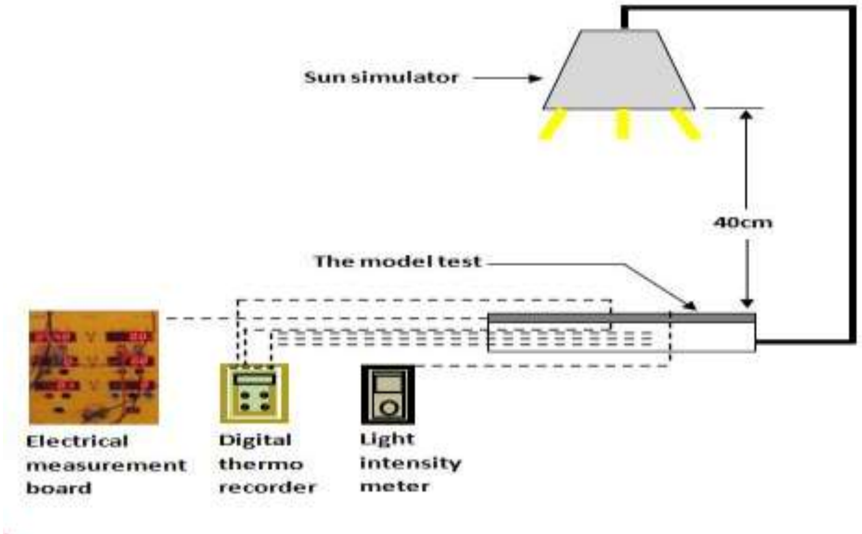


Fig (2) Thermocouples location



(a)



(b)

Fig (3): (a) The complete system, (b) Schematic diagram.

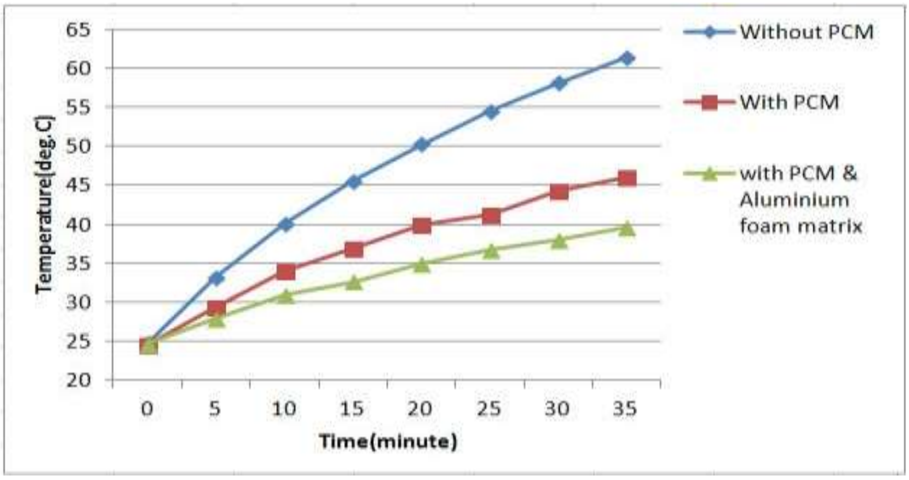


Fig (4) Effect of using PCM and PCM/aluminum foam matrix on PV panel temperature at (G=800W/m^2) .

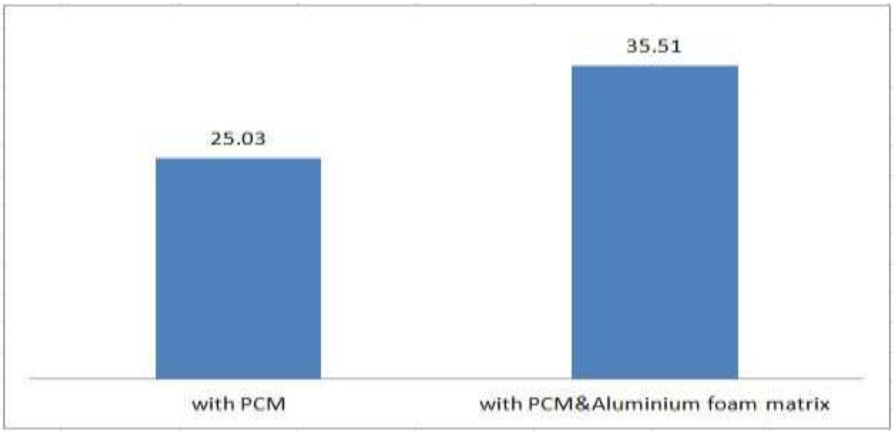


Fig (5) : Percentage of drooping PV panel temperature comparison with PV panel without PCM at (G=800W/m^2) .

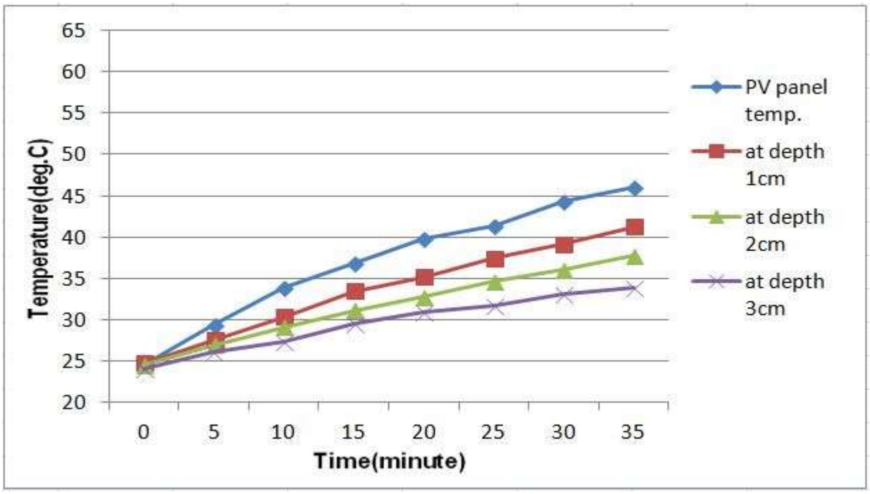


Fig (6) : Thermocouples reading for compound PV/PCM only at (G=800W/m^2).

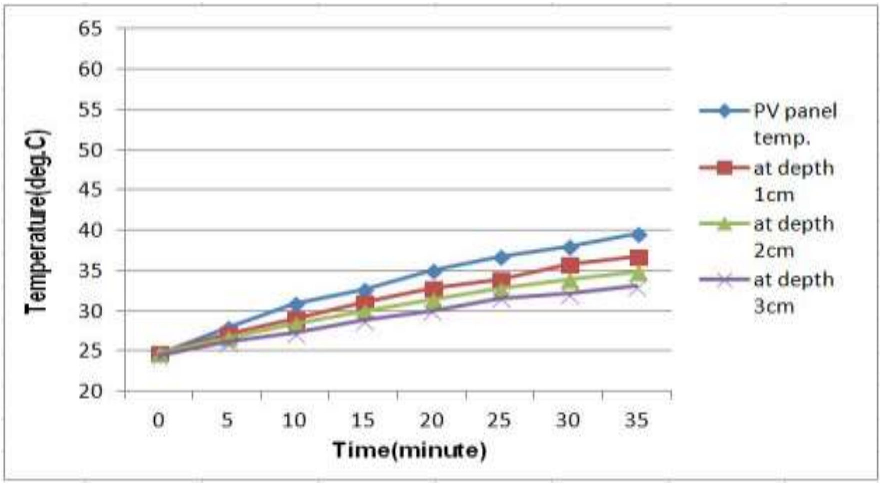


Fig (7) : Thermocouples reading for compound PV/PCM & aluminum foam matrix at (G=800W/m^2).

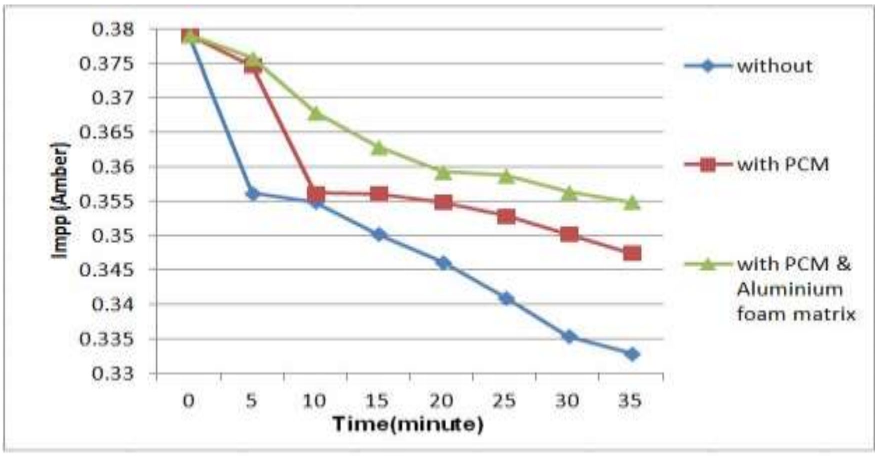


Fig (8) : Effect of using PCM and PCM/aluminum foam matrix on Impp of PV panel at (G=800W/m^2) .

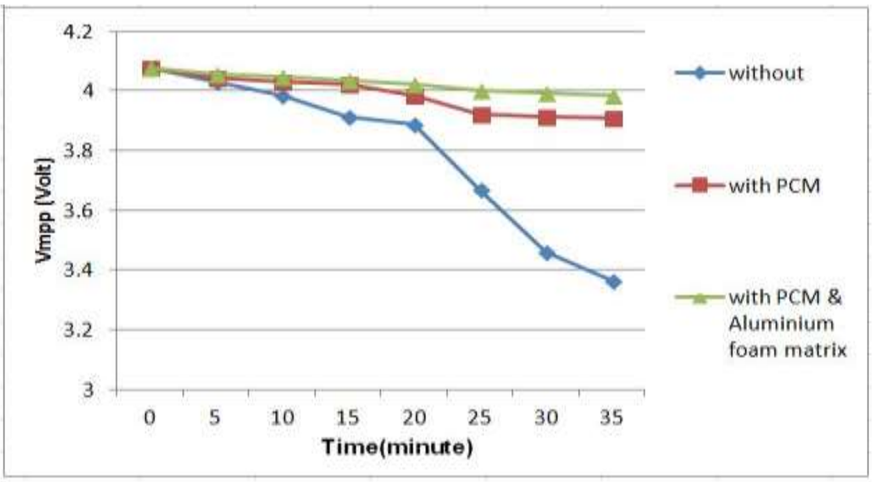


Fig (9) : Effect of using PCM and PCM/aluminum foam matrix on Vmpp of PV panel at (G=800W/m^2).

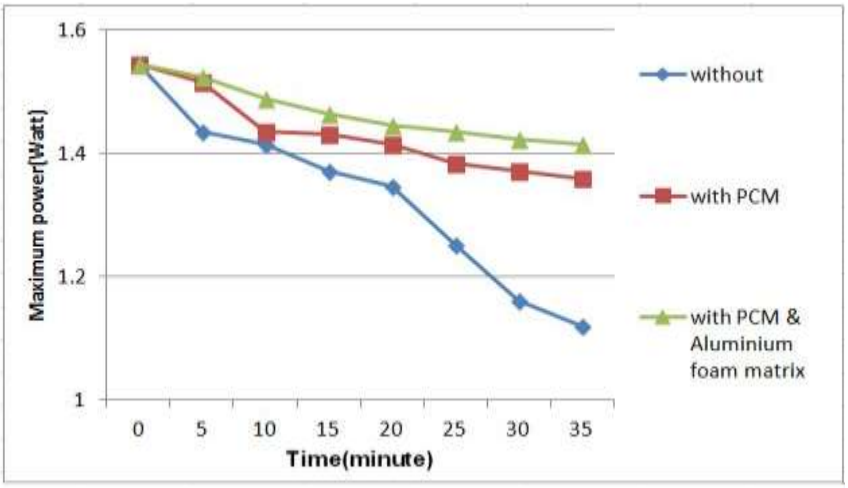


Fig (10) : Effect of using PCM and PCM/aluminum foam matrix on PV panel maximum power at ($G=800W/m^2$) .

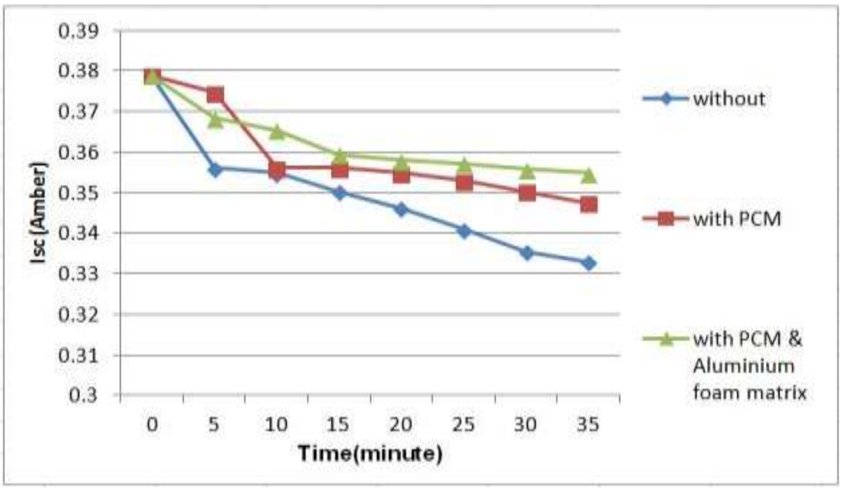


Fig (11) : Effect of using PCM and PCM/aluminum foam matrix on Isc of PV panel at ($G=800W/m^2$) .

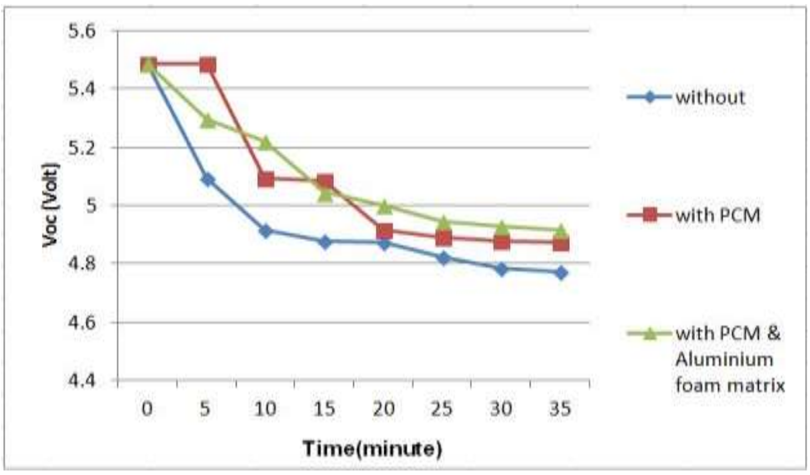


Fig (12): Effect of using PCM and PCM/aluminum foam matrix on Voc of PV panel at ($G=800W/m^2$).

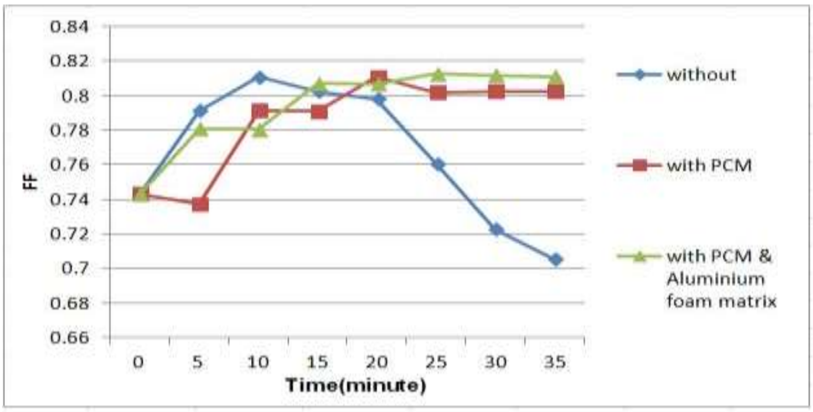


Fig (13) Effect of using PCM and PCM/aluminum foam matrix on PV panel fill factor at (G=800W/m^2) .

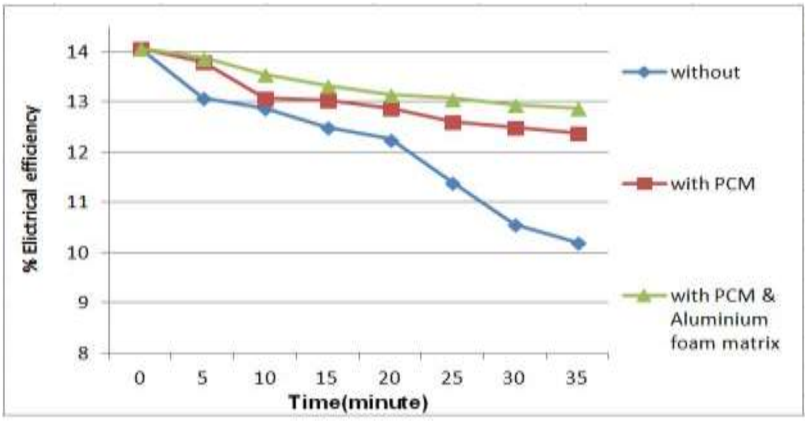


Fig (14) Effect of using PCM and PCM/aluminum foam matrix on PV panel electrical efficiency at (G=800W/m^2) .

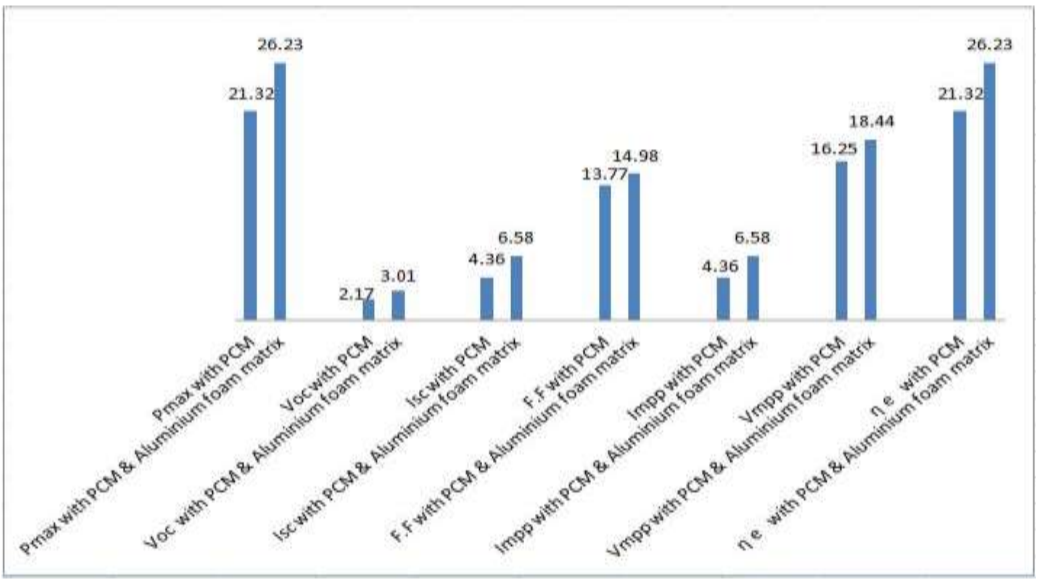


Fig (15) percentages of increasing PV panel electrical performance comparison with PV panel without PCM at (G=800W/m^2).

REFERENCES

Bauer, C.A., and Wirtz, R.A. , "Thermal characteristics of a compact, passive thermal energy storage device", ASME Heat Transfer Div. Publ. HTD, 366, 283-289, 2000 .

C. H. Cox, III and P. Raghuraman, "Design Consideration for Flat Plat Photovoltaic/Thermal Collectors", Solar Energy, Vol.35, pp.227-241, 1985.

Chi, P., Xie, Y., Yu, J., and Yang, X., "Experiment and analysis for cold charging process of new energy storage device", Journal of Beijing University of Aeronautics and Astronautics, 37, 1070-1075, 2011 .

Cui, H.T., "Experimental investigation on the heat charging process by paraffin filled with high porosity copper foam", Appl. Therm. Eng.,39, 26-28, 2012 .

Jinghua, J., Yingying, Z., Aibin, M., Donghui, Y., Fumin, L., Jianqing, C., Jun, S., Song, D., "Preparation and performances of bulk porous Al foams impregnated with phase-change-materials for thermal storage", PNSC Progress in Natural Science: Materials International, 22, 440- 444, 2012 .

K. Boomsma, "On the effective thermal conductivity of a three-dimensionally structured fluid-saturated metal foam," International Journal of Heat and Mass Transfer, vol. 44, no. 4, pp. 827-836, Feb. 2001.

Maria C. Browne, Brian Norton, Sarah J. McCormack, "Heat retention of a photovoltaic/thermal collector with PCM", Solar Energy, 133, 533-548, 2016 .

N. Tsolas, "Thermal Spray Forming of High-Efficiency Metal-Foam Heat Exchangers," M.Sc. thesis, University of Toronto, 2010, Toronto. Copyright © 2012 .

Py, X., Olives, R., Mauran, S., "Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material", International journal of heat and mass transfer., 44, 2727-2737, 2001.

Sheng, Q., Xing, Y., and Wang, Z., "Preparation and performance analysis of metal foam composite phase change material", Journal of Chemical Industry and Engineering, 64, 3565-3570, 2013.

Tong, X., Khan, J.A., and Amin, M.R., "Enhancement of solidification heat transfer by inserting metal-matrix into phase change material", 8, Numerical Heat Transfer Applications , 30(2):125-141, 1995 .

Zalba, B., Marin, J. M., Cabeza, L. F., and Mehling, H., "Review on thermal energy storage with phase change Materials", heat transfer analysis and applications, Appl. Therm. Eng., 23, 251-283, 2003 .

Zhang, T., and Yu, J., "Experiment of solid-liquid phase change in copper foam", Journal of Beijing University of Aeronautics and Astronautics, 33, 1021-1024, 2007.