Improving electrical energy and producing thermal energy in solar photovoltaic system by integrating phase change materials

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Abstract. Solar energy is a natural source that provides clean and renewable energy, which supplies two types of energy: thermal energy and photovoltaic energy. Whereas, the most effective way to exploit this energy is photovoltaic cells. However, for all the incident solar radiation, the solar panels can absorb a limited quantity of energy. While, the rest of radiation energy gets lost as heat, that increases the temperature of the photovoltaic cells, this is the reason why the productivity of electricity is decreased. Therefore, to exceed this issue and benefit from the two sources of sun radiation, a hybrid thermo-electrical system is proposed. The system is a solar panel surrounded by the phase change material that can absorb the temperature to increase the efficiency of solar system and use this energy to produce a hot water.

Keywords: PCM; solar energy; hybrid; thermo-electrical energy.

1 1. Introduction

Solar energy is the most widespread and distributed energy in the world, which is presently one of the greatest renewable and green energy sources, has been extensively focused and investigated for producing heat and electricity. Using solar energy in our standard of living can be decreasing energy costs and protect the environment. Therefore, the photovoltaic (PV) cells exploit the photovoltaic effect to produce direct current by absorbing of solar radiation. This effect allows cells to convert light energy from photons into electricity through a semiconductor material carrying electric charges. However, only a limited sun radiation on a (PV) can be transformed into electrical energy, the rest of this radiation is transformed into a heat, which is not only a waste of energy but also affect the PV cell converting solar energy into electricity and decrease their productivity[1]. For that reason, we proposed hybrid system based on the Phase change materials this system can provides an electrical energy from the photovoltaic cells with more productivity and thermal energy from the heat of photovoltaic panel and directly from sun radiation, which produce hot water. Phase change materials (PCMs) are materials that have a large capacity to store energy in the form of latent heat, the PCM changes phase (it liquefies) by absorbing heat from the ambient atmosphere and when the temperature drops, it becomes solid by restoring the stored heat. In this study, a numerical investigation pretend the increase the efficiently of solar cells by using the PCM that can be decreasing the temperature in the PV this energy can be used to produce the hot water. Therefore, a rectangle form of PCM has chosen and a model of this prototype are required, the results are very promising.

2. Experimental setup

2.1. Model of the thermal solar energy system

The proposed hybrid thermo-photovoltaic system is shown in Figure 1.

![Fig. 1: Solar heater that uses a PCM](image)

The system can produce electrical and thermal energy from the sun and, thus, enhance solar energy
systems be enabling electrical energy production when solar panels have a constant temperature. The system can also use extra indirect temperature from panels and extra direct temperature from air and the sun to produce and store thermal energy via the PCM integrated into the solar collectors (1).

The proposed solar energy system (Figure 3) has the following components:
- The solar collector is the main component, and it produces electrical energy on the basis of the PV effect. The collector has dual functions; the first is the conversion of energy from the sun into electrical energy, and the second is the conversion of energy from the PV collector into thermal energy in the PCM for storage and later use to produce hot water.
- The PCM tank (1,2) is a critical element of thermal energy production, and it is designed to store heat and release it when needed or in the absence of the sun. In addition, using PCMs in the systems allows the use of reduced tanks volume without reducing the energy stored. Therefore, energy capacity is based on thermal stratification process that the warm water will always settle on top of cold water.

This system aims to support and complement the previous systems proposed, and therefore develop a perfect and homogeneous system for the heating and storage of thermal energy.

2.2 Physical model
The heat transfer (3) in the PCM layer is achieved by phase change. In fact, there are diverse methods for heating as radiation and conduction. It assumed that the PCM volume variation during the change phase was negligible. In addition, the PCM is isotropic, homogeneous and the thermo-physical properties are assumed constants (4). In this way, we consider the system described in Figure 2.

![Fig. 1: Presentation of the PV/PCM system, boundary conditions and geometry (dimensions in mm)](image)

The PCM unit has two types of plate the horizontal plate is rectangular shape (5) that is filled by paraffin with length L = 1.5 m and width l=0.1m, and vertical plate is rectangular shape (5) that is filled by paraffin with length L = 1 m and width l=0.1m (Figure 4).

The objective is to have a tool for predicting the performance of a hybrid system based on solar panel integrate the PCM. We consider a photovoltaic cell as a rectangle the PCMs placed in a rectangular attachment of which all the faces of the rectangle are assumed to be adiabatic except that in contact with the photovoltaic cell the variation of the volume during the change of phase of PCM is considered negligible. The proposed system as shown in figure 2:

![Fig. 2: Presentation of the PV/PCM system, boundary conditions and geometry (dimensions in mm)](image)

### Table 1. Thermal properties of PCM (3) (fission temperature)

| Property                  | Unit       | Value   |
|---------------------------|------------|---------|
| Volume Mass (Kg/m³)       |            | ~820    |
| Thermal Capacity (KJ/Kg °C)|           | ~2 (liquid) |
| Thermal Conductivity (W/m.°C)|     | ~1.9 (solid) |
| Fusion Temperature (°C)   |            | ~64     |
| Latent Heat (KJ/Kg)       |            | ~230    |

The boundary conditions and the gravity direction used for numerical simulation are depicted. At the top and the bottom surfaces, an adiabatic wall is defined. To avoid heat exchange between PCM and air, the interface domain is considered as a wall(6). The adiabatic boundary condition stopped heat dissipation that is coming from the fluid heat transfer during the charging process. It is assumed that the top surface of the PCM plate receives hot temperature when the bottom one receives cold temperature.

The boundary conditions are indicated in Figure 4 (7).

### Table 2. Initial and boundary conditions

| Condition                  | Initial condition at t=0 |
|----------------------------|--------------------------|
| T(x,0)=T₀                 |                          |
| 0                          | Boundary condition at x=E (the adiabatic boundary) |
| T(q₁,0)=Tᵣ                | Boundary condition at x=q(0) (melting front) |
| –K²∂x/q₁∂x                | Boundary condition at x=0 (the boundary which is subject to constant heat flux w) |

3. Numerical model
3.1 Governing equations

The natural convection effect in liquid phase helps to provide the governing equations for transient analysis of the PCM melting process include the mass conservation equation, the momentum conservation equation and the energy conservation equation (8).

Under assumption of laminar and incompressible flow, appealing the Boussinesq approximation in modelling the buoyancy force (9), the governing equations can be written as follows (10).

Mass conservation equation:
\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  
(1)

\((u, v)\) velocity components in x and y directions respectively.

Momentum conservation equation:
\[ \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \rho \beta \theta (T - T_m) + \frac{(1 - \rho_f)}{(\rho_f - \rho)} \rho_m u \]  
(2)

Energy conservation equation:
\[ \frac{\partial (\rho H)}{\partial t} + \frac{\partial (\rho u H)}{\partial x} + \frac{\partial (\rho v H)}{\partial y} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  
(3)

With: \(\rho\) the pressure, \(\theta\) the density. \(\beta\) coefficient of thermal expansion, \(\mu\) dynamic viscosity, \(g\) acceleration of gravity, \(F_l\) liquid fraction, \(A_m\) constant of the pasty zone and \(\xi\) real number of low value \((10^{-4})\) to avoid division by zero, \(T\): temperature.

Projection on x:
\[ \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \rho \beta \theta (T - T_m) + \frac{(1 - \rho_f)}{(\rho_f - \rho)} \rho_m u \]  
(4)

Projection on y:
\[ \frac{\partial (\rho H)}{\partial t} + u \frac{\partial (\rho H)}{\partial x} + v \frac{\partial (\rho H)}{\partial y} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  
(5)

With \(H\): specific enthalpy and \(k\): thermal conductivity.

The constant of the pasty zone \((A_m)\) measures the velocity loss in the zone where phase change takes place. Once the transition is higher, the zone speed being solidified tends to zero fast. In contrast, if the \(A_m\) is lower the solidification rate is increased and the liquid fraction value is reduced \((\text{order of } 10^{-4})\).

3.2 Results and discussion

The proposed solar power system aims to improve electrical energy production using a phase change material (PCM) that gets rid of the increase in undesirable temperatures and uses thermal energy to heat water. For this reason, a numerical study based on MATLAB and ANSYS software is used to get the results as a function of enthalpy, temperature, time, stocked energy and melting evolution. To validate the model, a comparison of the predicted temperature in the numerical simulation with the experimental results is performed. The system geometry, material parameters and boundary conditions are as close as possible [9].

3.2.1 Enthalpy Vs temperature in PCM (fusion vs solidification)

The obtained results show that PCMs absorb large amounts of heat, followed by a temperature increase until they reach the phase change temperature (melting temperature). However, PCMs keep absorbing heat until all the material is converted to the liquid phase. As a result, this simulation can describe the PCM behaviour (11).

Consequently, the enthalpy changes as a function of temperature, and the system absorbs or releases energy until the steady state is achieved, as shown in Figure 5.

Figure 5 shows the enthalpy evolution \(H\) as a function of time

Fig. 2: the evolution of enthalpy H as a function of time

When the PCM layer is integrated into the module, the PCM absorbs thermal energy from the PV system, and its temperature is decreased compared to the system without the PCM, as shown in Figure 6:
The effect of the front surface of system temperature is shown in Figure 6. It can be understood that the expected temperatures on the front surface of PV/PCM system are of a consistent form. After some time the temperature of the MCP increasing that caused the productivity of the hot water, although the temperature of panel PV still constant the front surface does not change significantly, however as less heat is lost from the system, the time necessary for the phase change material melting is reduced. The temperatures increase quickly for the first 3 min, the temperatures on the front surface of PV/PCM system then still basically constant through the PCM transition and then increased quickly at phase change achievement. After complete melting, the liquid PCM is higher than that for the solid PCM the amount of temperature rise is slowly than that during the solid stage. The temperatures aluminium plate is cooled by the water and on the front surface of the PV/PCM system.

3.2.1. Simulation using finite element method

In order to improve the production and storage of thermal energy, a 2D numerical simulation using ANSYS FLUENT software (13)(14) based on finite volume approach is proposed. In addition, the paraffin PCM is used for the melting process that had a very high latent heat and can be found everywhere.

Assuming that x = 0 at the outer wall of the plate, the plate is initially at $T_{in} = 57 \, ^\circ C$, the fluid temperature of the heat transfer $T_{in} = 69 \, ^\circ C$. The phase change temperature of the paraffin $T_f = 64 \, ^\circ C$.

The geometrical model is uniformly meshed using symmetric square cells as depicted in Figure 10. A very fine mesh was applied to the 2D rectangular PCM which predicting correctly its features. The selected elements are 1056 and the nodes are 1139.
4. Conclusion

In this study, the hybrid thermophotovoltaic system is based on PCMs that can produce electricity, which are surrounded by PCMs that can absorb heat in order to increase the efficiency of the solar power system and use the absorbed thermal energy to produce hot water. For this reason, a numerical study based on MATLAB and ANSYS software is employed to attain the results as functions of enthalpy temperature, time, stocked energy and melting evolution. To validate the model, a comparison of the predicted temperature in the numerical simulation with the experimental results is performed. The system geometry, material parameters and boundary conditions are as close as possible.

The proposed system is able to store energy in the collector and in the tank, which is why the system without PCM realises the energy faster than the proposed system. Therefore, the overall operation of the heating system can accelerate the heating; if the tank is exhausted, the collector quickly heats the water using the stocked energy in the PCM and energy from the sun.

The numerical analysis and the results of the experiment show that the integration of the PCMs makes it possible to reduce the temperature of the photovoltaic module by 30°C; this decrease improves the efficiency of the PV module. The fundamental objective of this work has therefore been achieved. However, there are some problems related to the problem of PCM volume change during integration with the photovoltaic module; if a stabilised form of the PCM is used, the problem will be solved.

References

1. Zhao J, Ji Y, Yuan Y, Zhang Z, Lu J. Energy-Saving Analysis of Solar Heating System with PCM Storage Tank. Energies. 2018;11(1):237.

2. Beemkumar N, Karthikeyan A, Keshava Reddy KS, Rajesh K, Anderson A. Analysis of Thermal Energy Storage Tank by ANSYS and Comparison with Experimental Results to Improve its Thermal Efficiency. IOP Conf Ser Mater Sci Eng. 2017;197(1).

3. Lohse E, Schmitz G. Experimental analysis of regularly structured composite latent heat storages for temporary cooling of electronic components. Heat Mass Transf und Stoffuebertragung. 2013;49(11):1565–75.

4. Mohammed MAP, Tarleton E, Charalambides MN, Williams JG. Mechanical characterization and micromechanical modeling of bread dough. J Rheol (N Y N Y). 2013;57(1):249–72.

5. Chan CW, Tan FL. Solidification inside a sphere - An experimental study. Int Commun Heat Mass Transf. 2006;33(3):335–41.

6. Tian Y, Zhao C-Y. Heat transfer analysis for phase change materials (PCMs). 2009;1–8.

7. Petrone G. CL and CG. Numerical simulation of pcm melting process. 2012;(July):469–74.

8. Verma S, Dewan A. Solidification modeling: Evolution, benchmarks, trends in handling turbulence, and future directions. Metall Mater Trans B Process Metall Mater Process Sci. 2014;45(4):1456–71.

9. Augspurger M, Udaykumar HS. A Cartesian grid solver for simulation of a phase-change material (PCM) solar thermal storage device. Numer Heat Transf Part B Fundam. 2016;69(3):179–96.

10. Gharebaghi M, Sezai I. Enhancement of heat transfer in latent heat storage modules with internal fins. Numer Heat Transf Part A Appl. 2008;53(7):749–65.

11. Saw CL, Al-Kayiem HH, Owolabi AL. Experimental investigation on the effect of PCM and Nano-enhanced PCM of integrated solar collector performance. WIT Trans Ecol Environ. 2013;179 VOLUME(December):899–909.

12. Benbrika M, Benbelhout M, Teggar M. Amélioration de l’ efficacité thermique d’ un chauffe-eau solaire par l’utilisation de matériaux à changement de phase (MCP). Int J Sci Res Eng Technol. 2015;Vol.4 pp.1(December).

13. Koller M, Walter H, Hameter M. Transient numerical simulation of the melting and solidification behavior of NaNo3 using a wire matrix for enhancing the heat transfer. Energies. 2016;9(3).

14. Asyraf WM, Vasu A, Hagos FY, Noor MM, Mamat R. Transient modelling of heat loading of phase change material for energy storage. 2017;01078.

15. Yadav A, Soni S. Simulation of Melting Process of a Phase Change Material (PCM) using ANSYS (Fluent). Int Res J Eng Technol. 2017;2395–56.