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Numerical investigation of the effects of a copper foam filled with phase change materials in a water-cooled photovoltaic/thermal system

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ABSTRACT

The purpose of the present study is to investigate the thermal performance of a photovoltaic/thermal system, integrated with phase change materials in porous medium. For this purpose, a metal foam was employed as porous medium and the performance of five different PCMs, as organic and inorganic, were examined as well. Moreover, the effects of different key parameters such as the mass flow rate, solar irradiance, inlet water temperature and inclination were studied. Finally, the simulation results were compared with a water-cooled photovoltaic/thermal without incorporating PCMs and porous medium, and thermal performance of the three PV/T cases were reported. The highest thermal efficiency of the system was reported as 83% in case of 0.02 kg s^{-1} mass flow rate and using Paraffin C22 as the storage material. In addition, the incorporation of porous medium resulted in better temperature distribution, and the porosity of 0.8 was resulted in higher thermal performance. Furthermore, the results were validated with an experimental study, and good agreement was reported. At last, the exergy analysis was applied on the system, and the results showed that the exergy efficiency of the PV/T module with metal foam filled with PCM was 16.7%.

1. Introduction

The share of renewable energy in the international sustainable development cannot be neglected. Increasing the global concerns in order to compensate the lack of fossil fuels resources for electricity production has paved the way for solar technologies, and exclusively, photovoltaic systems. Current technology allows solar customers to achieve electrical efficiency of 20 percent and the excess of energy will result in rising the system's temperature. Photovoltaic panels will endure temperature enhancement up to specified limits, however as the temperature exceeds these limits, the electrical efficiency of the panels will be decreased [1]. By introducing photovoltaic/thermal systems, recycling absorbed heat and reducing panel's temperature became possible. Furthermore, recent studies have investigated the performance improvement of such systems.

The primary investigations on photovoltaic/thermal systems were performed in 1970s by Kern and Russel [2]. Since then, the photovoltaic/thermal systems have been an interesting concept for researchers to investigate the improvement of the thermal and electrical performance. Number of researches investigated various parameters such as the thermal absorber design items, the effect of glass cover, pressure drop, mass flow rate and the connection between absorber plate and photovoltaic panel. A valuable investigation was performed by Santbergen et al. [3] who studied the performance of different PV/T systems and the effect of cover layer and different types of cooling fluid on the performance. As a result, the water cooled PV/T systems were recognized to be more effective, and the thermal and electrical efficiencies were reported. In 2016, Khanjari et al. [4] presented a numerical study on PV/T water cooled system using Ag-water and Al-water nanofluids. Moreover, a CFD analysis was conducted on a water-cooled PV/T system using nanofluids by Khanjari et al. [5] in 2016. An experimental investigation was performed by Waeli et al. [6,7] on a PV/T system using PCM and a mixture on Nano SiC-water to enhance the thermal performance of the system. Furthermore, a numerical study was performed by Rejeb et al. [8] to investigate the effect of Nano fluid concentration on thermal performance of a PV/T system. In addition, Lari and Sahin [9] investigated a PV/T using nanofluid for residential applications in Saudi Arabia.

Recent studies have focused on the developed PV/T systems, incorporating with phase change materials as the heat storage, and Kapsalis and Karamanis [10]presented a review study in case of implementing PCM materials in solar technologies. A novel investigation

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Nomenclature

Q_u	efficient collected heat (W)
η	efficiency
G	solar radiation intensity (Wm^{-2})
A	area (m^2)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
τ	transmissivity
C_p	specific heat capacity ($KJ\ Kg^{-1};K^{-1}$)
T	temperature (K)
Nr	number of risers
Lr	length of risers (m)
t	panel thickness (m)
k	permeability (m^{-1})
ε	porosity
β_r	temperature coefficient ($°C^{-1}$)

Subscripts

STC	standard test condition
out	outlet
in	inlet
Panel	solar panel
th	thermal
el	electrical
el,n	nominal electrical
c	collector
g	glass cover

on PV/T system using phase change materials incorporating thermoelectric materials was performed by Cui et al. [11] in 2016. An experimental study on PV/T systems using PCMs was conducted by Harikrishnan et al. [12] and the performance of a composite PCM was compared with a mixture of Lauric acid and stearic acid. Ho et al. [13] presented a novel numerical model to investigate the improvement of a PV system. In this regard, two water-saturated microencapsulated phase change material (MEPCM) layers were used, and the effects of MEPCM were evaluated. The results showed that the module output could be increased by 2.03 percent during the summer. Hasan et al. [14] in 2015, experimentally investigated a PV/T system in two different climates. Two identical PV/T units were studied in Dublin, Ireland and Vehari, and Pakistan. Calcium chloride salt and a eutectic mixture, palmitic and capric acid, were investigated as the phase change materials. Browne et al. [15], in 2016, investigated a PV/T system with phase change materials. A thermosyphon closed-loop flow was designed to circulate water through a heat exchanger. The eutectic mixture, capric and palmitic acid, was utilized as PCM in this study, and the results were compared with a simple PV/T in order to determine the effects of employing phase change materials. The previous studies were focused on the utilizing of PCMs as thermal storages. However, the thermal conductivity of the PCMs in phase change process is not significant. For this reason, the implementation of porous medium in PV/T systems would improve the heat dissipation, and consequently, increase the thermal performance.

In addition, a number of researchers have studied the phase change process through porous mediums. Cui [16] and Beckermann and Viskanta [17] focused on the heat transfer improvement of phase change materials by using metal foam. Tao et al. [18] investigated the heat transfer of a porous medium filled with phase change materials, using the Lattice Boltzmann method. Zhou and Zhao [19] utilized the phase field method to analyze the heat transfer of phase change material in a metal foam. Krishnan et al. [20] presented a two-temperature model to evaluate the performance of a metallic foam, filled with PCM. The Darcy-Brinkman equations were used in order to investigate the effect of metal foam. Another numerical study was performed by Du and Ding [21] on the heat transfer of a porous medium incorporating phase change material. An aluminum foam with porosity of 0.8 was used as porous medium and paraffin wax was incorporated as the phase change material. Atal et al. [22] conducted an experimental study to investigate the effects of porosity on the improvement of thermal conductivity through phase change process. Two porous mediums with different porosities of 0.95 and 0.77 were studied and the thermal performance and charge/discharge period were reported.

The previous studies were focused on the implementation of phase change materials in PV/T systems as thermal storage. The implementation of phase change materials, as thermal storage, would improve the PVT systems‘ thermal and electrical efficiencies. However, a major disadvantage of phase change materials is the low thermal conductivity during the phase change process. For this reason, as the novelty of this study and also a beneficial solution, the implementation of a metallic porous mediums was considered. In addition, an exrgy analysis was conducted for the mentioned system. For this aim, a CFD model was developed to investigate the effects of five PCMs as well as the effects of copper foam as the porous medium. Furthermore, the effects of the mass flow rate, solar irradiance, and inlet temperature and inclination angle were studied, and the electrical and thermal efficiencies were calculated. Finally, the results were validated with the experimental investigation of Browne et al. [15].

2. Methodology

2.1. Model description

The present study demonstrates an investigation on a photovoltaic/thermal system, incorporating with phase change materials, in order to improve the overall performance. For reaching this target, a photovoltaic/thermal model including a glass-covered photovoltaic panel, an absorber plate, a sheet-and-tube heat exchanger and a container, filled with PCM, were taken into account. The information about the components are given in Table 1.

As it can be seen in Fig. 1, a sheet-and-tube heat exchanger was attached to the absorber plate. In order to reduce the calculation time and due to the symmetry of the model's geometry, the model was simplified, and only one riser tube was investigated. Furthermore, the simulation was focused on thermal investigations, the electrical performance of photovoltaic panel was not considered in the present study, and the effect of photovoltaic panel was considered as the boundary condition. For this purpose, the desired geometry was designed in the Solidworks software, and in order to continue the solution process, the

Table 1
The specifications of the system‘s components.

Photovoltaic panel	η_r: 14.91% @STC
	β_r: 0.004 $°C^{-1}$
	τ_g: 0.9
Absorber plate	Length: 1.6 m
	Width: 1 m
	Material: Copper
	t: 0.002 m
Sheet-and-tube exchanger	Tube outer diameter: 0.01 m
	Tube thickness: 0.001 m
	Center-to-center tube space: 0.1 m
	Nr: 20
	Lr: 1.6 m
	Material: Copper
Container	Length: 1.6 m
	Width: 1 m
	Material: Copper