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Optimization and parametric analysis of a nanofluid based photovoltaic thermal system: 3D numerical model with experimental validation

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ABSTRACT

In this study, the effects of ZnO/water nanofluid and pure water as working fluids on the electrical and thermal energy efficiencies of a photovoltaic thermal system (PVT) are numerically investigated. The governing equations are discretized and solved using the pressure-based finite volume method by the ANSYS Fluent 16.2 software. The 3D numerical model is validated by comparing the simulation results with those of the measurements. The experiments are performed on selected days in August and September at the Ferdowsi University of Mashhad, Mashhad, Iran. To investigate the reliability of the measurements, an uncertainty analysis is performed for the experiments. The effects of the important operating parameters on the electrical and thermal energy efficiencies of the PVT system with ZnO/water nanofluid are studied. Moreover, the Taguchi method is applied to determine the optimum performance of the nanofluid based PVT system. The considered parameters include: absorbed solar irradiation, wind speed, ambient temperature, coolant inlet temperature, coolant mass flow rate, and nanoparticles mass fraction in the ZnO/water nanofluid. Based on the results of this study, reducing the coolant inlet temperature from 40 °C to 20 °C enhances the thermal energy efficiency of the nanofluid based PVT system by 16.21%. Moreover, it is found that the considered parameters in this study have slight effects on the electrical energy efficiency of the PVT system. The Taguchi analysis shows that the coolant inlet temperature is the most effective parameter on the efficiency of the nanofluid based PVT system.

1. Introduction

A common photovoltaic module (PV) is a technology to convert the solar energy into electricity, directly. A PV module can absorb about 90% of the incoming solar irradiation [1], whereas its electrical efficiency is in the range of 4–17% [2,3]. Hence, a significant portion of the absorbed solar irradiation is converted into heat and; consequently, the temperature of the photovoltaic cells increases. As a result, the open circuit voltage decreases which, in turn, reduces the electrical efficiency of the PV module [4]. The increase of the cells temperature can also damage the structure of the PV cells [5]. Hence, the cooling of the PV module is essential. Furthermore, by adding a heat recovery system to a PV module, the waste thermal energy can be extracted. This system is known as a photovoltaic thermal system (PVT).

Many parameters can affect the performance of PVT systems. They can be divided into two categories: design vs. operating parameters. The important design parameters include: photovoltaic cells type [6], thermal collector structure [7,8], working fluid type [9,10], and the use of phase change martials (PCMs) [11]. On the other hand, the important operating parameters are: absorbed solar irradiation by the photovoltaic cells, wind speed, ambient temperature, temperature of working fluid at the inlet of collector (coolant inlet temperature), and coolant mass flow rate. In order to determine the optimum conditions of the PVT system, an investigation of the operating parameters are required.

Numerous studies have been performed in the literature on the effects of different parameters on the performance of a PVT system. Daghigh et al. [12] collected the studies regarding the fluid-based (water, water/air and refrigerant) PVT systems in a review article. Bhattarai et al. [13] evaluated a 1D transient model of a water based sheet-and-tube PVT system using both experiments and simulations. They also compared the performance of the PVT system with a conventional solar collector and found the thermal energy efficiency of the PVT system and solar collector to be 58.70% and 71.50%, respectively. The electrical energy efficiency of the PVT system was about 13.69%. Bahaidarah et al. [14] presented a numerical and experimental study to evaluate the effects of surface temperature of water cooling system on the system performance for hot climatic conditions. They found that using the active cooling system decreases the temperature of the photovoltaic cells by about 20% and increases the electrical energy

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Nomenclature

A	area (m^2)
C_P	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
d	diameter (m)
$\dot{E}$	power (W)
FF	fill factor
$\dot{G}$	solar irradiation rate ($W\,m^{-2}$)
I	electrical current (A)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	repetitions in a trial
NE	minimum number of trials
NL	number of levels
NP	number of parameters
P	pressure (Pa)
R	arbitrary function
T	temperature (K)
V	velocity (m/s)
y	response

Greeks

α	absorptivity
δ	uncertainty
η	energy efficiency (%)
κ_B	Boltzmann constant
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
υ	arbitrary parameter
ρ	density ($kg\,m^{-3}$)
τ	transmissivity
ϕ	nanoparticles volume fraction

Subscripts

amb	ambient
bf	base fluid
c	collector
el	electrical
g	glass cover
in	inlet
n	nanoparticle
nf	nanofluid
oc	open circuit
out	outlet
ov	overall
r	standard test condition
s	solid
sc	short circuit
th	thermal
w	wind

efficiency by 9%. Hazami et al. [15] numerically and experimentally analyzed the performance of a water based PVT system for both passive and active techniques. They concluded that the maximum instantaneous electrical and thermal energy efficiencies are 15% and 50% for the active technique, respectively. Furthermore, the annual thermal energy efficiency of the system in the active technique was found to be about 5% higher than that of the passive technique.

Yazdanifard et al. [16] studied the performance of a water based PVT system with and without a glass cover in the laminar and turbulent flow regimes. They also investigated the effects of solar irradiation, Reynolds number, packing factor, collector length, pipes diameter, and number of pipes on the efficiency of the system. They obtained a higher total energy efficiency for the turbulent regime compared to that of the laminar. Moreover, they found that increasing the solar irradiation and packing factor enhances the total energy efficiency of the system in both laminar and turbulent flow regimes. Chow et al. [17] numerically and experimentally investigated the performance of a water based PVT system with and without a glass cover. They evaluated the effects of six parameters including PV cell efficiency, packing factor, ratio of water mass to collector area, solar irradiation, wind speed and ambient temperature. They found the energy efficiency of the glazed PVT system (with glass cover) to be higher than that of the unglazed PVT system (without glass cover). Furthermore, the increase of PV cell efficiency, packing factor, ratio of water mass per unit area of the collector, and wind speed were found to be favorable parameters for the unglazed system. On the other hand, the increase of solar irradiation and ambient temperature were the favorable parameters for the glazed system. Corbin and Zhai [18], numerically and experimentally investigated the efficiency of a water based building integrated photovoltaic thermal system (referred as BIPVT). They obtained the thermal and overall energy efficiencies of 19% and 34.9%, respectively. They also presented a correlation that predicts the electrical efficiency based on solar irradiation, coolant inlet temperature, and ambient temperature. In a 3D numerical model, Siddiqui et al. [19] studied the electrical and thermal performance of a water based PVT system under different operating conditions. They considered five parameters including absorbed solar irradiation, ambient temperature, thermal contact resistance between PV module and heat exchanger, fluid inlet temperature and velocity. They claimed that an increase of the solar irradiation at a constant ambient temperature and an increase of the ambient temperature at a constant solar irradiation have negligible effects on the performance of a PVT system.

Dispersion of metal-oxide nanoparticles in a fluid can increase the thermal conductivity and convection heat transfer coefficient of the base fluid [20,21]. Hence, an effective method to improve the efficiency of a PVT system is the use of nanofluids. This, however, leads to several drawbacks such as high cost of nanoparticles, limited time of stability, and pressure drop in the collector [22,23]. Many attempts have been performed to study the effects of nanofluids on the performance of PVT systems. Michael and Iniyan [24] performed an experimental analysis to evaluate the effects of using CuO/water nanofluid as the working fluid on the performance of a PVT system. They found that using nanofluid with 0.05% volume fraction can increase the thermal energy efficiency by 45.76% compared to that of the base fluid (water). Ghadiri et al. [25] investigated the thermal and electrical efficiency of a PVT system using Fe_3O_4/water nanofluid with 1% and 3% by weight (wt%) under constant and alternating magnetic fields. They performed their experiments at an indoor condition using a solar irradiation simulator. Their results showed 76% improvement in the overall energy efficiency of the system for a 3 wt% nanofluid compared to that of pure water. Al-Shamani et al. [26] performed an experimental study of a rectangular tube absorber PVT system with various types of nanofluids (SiO_2/water, TiO_2/water and SiC/water) under tropical climate conditions. They found maximum electrical and overall energy efficiencies of 13.52% and 81.73%, respectively, for SiC/water nanofluid at a mass flow rate of 0.17 kg/s. Elmir et al. [27] numerically evaluated the performance of a PVT system using Al_2O_3/water nanofluid. They investigated the effects of nanoparticle volume fraction and Reynolds number on the heat characteristics of the system. Their results indicated a linear variation of the modified average Nusselt number versus the nanoparticle volume fraction. Moreover, for a Reynolds number of 5 (low Reynolds number), increasing the nanoparticle volume fraction from 0% to 10% enhanced the heat transfer rate by 27%. Rejeb et al. [28] numerically considered the use of Al_2O_3 and Cu nanoparticles by