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Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions

Ali Najah Al-Shamani [a,b,*], K. Sopian [a,*], Sohif Mat [a], Husam Abdulrasool Hasan [a], Azher M. Abed [a], M.H. Ruslan [a]

[a] Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia
[b] Al-Musaib Technical College, Al-Furat Al-Awsat Technical University, 51009 Babylon, Iraq

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ABSTRACT

The flat plate photovoltaic thermal (PVT) collectors can be classified into the type of working fluids used namely the water based PVT collectors, air based PVT collectors and combination of water/air PVT collectors. However, low thermal conductivity of the working fluids has always been the primary limitation in the development of energy-efficient heat transfer fluids, and higher collector performance. To overcome this limitation, there is a strong motivation to improve the heat transfer of fluids with higher thermal conductivity. This new generation of heat transfer fluids called nanofluids consists of suspended nanoparticles and has higher suspension stability compared to the millimeter or micrometer size nanoparticles. Thus, the heat transfer characteristics will be enhanced by using nanofluids. The PVT collector has been designed, fabricated and tested outdoor under the Malaysia tropical climate conditions. The PVT collector consists of specially designed rectangular tube absorber (stainless steel material, height of 15 mm, width of 25 mm and thickness of 1 mm) attached under the photovoltaic module. The PVT collector was experimentally tested with different types of nanofluids (SiO_2, TiO_2 and SiC). The results indicated that the PVT collector with SiC nanofluid has the highest combined photovoltaic thermal (PVT) efficiency of 81.73% and PVT electrical efficiency of 13.52% with the best overall energy coefficient (COE) of 0.93 has been achieved at a flow rate of 0.170 kg/s and solar irradiance levels of 1000 W/m^2, followed by PVT-TiO_2 nanofluids, PVT-SiO_2 nanofluids, and PVT-water respectively.

1. Introduction

Combining photovoltaic and thermal collectors for the simultaneous production of both heat and electricity into one compact unit is an efficiency method of utilizing solar energy. This compact unit is also known as the photovoltaic thermal (PVT) collector [1]. The photovoltaic thermal collector has several advantages, including high energy conversion efficiency, lower life cycle cost, and saving of space as compared to PV and solar thermal systems installed separately. Furthermore, the usage of nanofluids which are a mixture of liquid (base fluid) and nanoparticles as the working fluids in liquid based PVT collector has been suggested and studied [2]. Conventional liquids used include water, glycol, and oil. The usages of nanofluid enhance the thermo-physical properties, such as thermal conductivity, density, specific heat and viscosity. Hence, resulting in enhancement of the heat convective heat transfer coefficients [3].

1.1. Water based PVT collector

The performance of the PVT collector depends upon various design parameters such as the absorber design configurations [4,5], collector length [6], collector depth [7], and also the PV module types [8]. The existing thermal absorbers available in the market for PVT were made from metals with, sheet and tube, roll bond, and box channel types. Generally, the most common configurations were the sheet and tube. The reason for this is due to its simple manufacturing processes and low thickness requirements of the absorbers. In addition to simulation studies, experimental studies on the performance evaluation of PVT collectors have been also carried out by many researchers [9–18].

* Corresponding authors at: Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

E-mail addresses: ali.alshamani@yahoo.com (A.N. Al-Shamani), ksopian@ukm.edu.my (K. Sopian).

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Nomenclature

A_c	collector area (m^2)	k	thermal conductivity (W/m K)
C_p	specific heat of water (J/kg K)	L	length of collector (m)
FF	fill factor of PV module	$\dot{m}$	mass flow rate (kg/s)
F	fin efficiency	Q_u	actual useful heat gain (W)
F′	collector efficiency factor	S	absorbed solar energy (W)
F″	collector flow factor	T_p	photovoltaic collector temperature (°C)
F_R	collector heat removal factor	T_a	ambient temperature (°C)
I	solar irradiance (W/m^2)	T_i	inlet fluid temperature (°C)
H	convective heat transfer coefficient (W/m^2 K)	T_o	outlet fluid temperature (°C)
h_r	radiative heat transfer coefficient (W/m^2 K)	U_L	overall collector heat loss coefficient (W/m^2 K)
W	Width of absorber tube	D	height of absorber tube
τ	Transmissivity	α	absorptivity

1.2. Nanofluids and nanoparticles

Thermal energy losses in solar collector to the surroundings can occur via conduction, convection, and radiation. Efficient heat transfer can contribute to the reduction of these losses. In recent years, the amount of experimental, theoretical, and numerical studies on the application of nanofluids in solar collectors have increased. Experimental studies on nanofluids application in solar collectors have been investigated by many researchers [19–24]. Elmir et al. [25] presented a numerical study of cooling a photovoltaic unit by using Al_2O_3–water nanofluid. They investigated the enhancement effects of heat transfer by applying the nanofluid in the PVT collector. They observed a significant heat transfer improvement in comparison to the pure water. Karimi and Rahimi [26] carried out an experimental study to investigate the effect of cooling the solar cells by using a Boehimite (AlOOH-*x*H O) as a cooling fluid and a 27% enhancement on the electrical performance has been observed.

In literature, most of the studies about the heat transfer improvement of a PVT system with pure water and there is a lack of information on enhancement of PVT using nanofluids. PVT technology has an inherent drawback of producing lower efficiencies compared to their individual units, due to lower absorption coefficient and higher thermal resistance. Meanwhile, nanofluids with properties leading to superior heat transfer characteristics encouraged the researchers to introduce these nanofluids into PVT collectors.

This paper presents an experimental study to investigate the performance of a water-based PVT with rectangular tube absorber and different types of nanofluids (SiO_2, TiO_2 and SiC). In addition, it also determines the maximum enhancement with cost analysis that can be achieved.

2. Experimental setups

2.1. The PVT system

An experimental set up was designed and fabricated to investigate the thermal and electrical performances of the PVT system using nanofluids. The setup consists of both PV module and PVT collector located side by side and the experimental data were collected simultaneously for both collectors. Other devices and instruments of the experimental setup were (a) pyranometer, (b) flow meter, (c) circulation pump, (d) anemometer cup, (e) DC electronic load, (f) water and nanofluid storage tanks and (g) thermocouples. The data acquisition consists of module ADAM 4019+ and is a set of intelligent sensor-to-computer interface modules containing a built-in microprocessor. The data-logger was connected directly to the computer system. The schematic diagram of the complete experimental set-up is shown in Fig. 1. The photograph of the set-up is shown in Fig. 2.

2.2. PV module and PVT collector

The PVT system has a closed-loop system, wherein the nanofluid that enters the tubes was continuously heated. The PVT collector and its absorber tubes design used in this study are shown in Fig. 3. The specifications of the PV module and PVT collector, with the assumed working conditions were presented in Tables 1 and 2.

2.3. Preparation of the nanofluids

Nanofluid is a special type of fluid that has suspension of nanoparticles in the base fluid. The two-step method was used to prepare the nanofluids. The two-step method include firstly by preparing the nanoparticles in a form of powder by physical or chemical methods, such as grinding, laser ablation, sol-gel processing, etc. and secondly suspending it in a base fluid [27]. The two-step method of production is cheaper, because nano powders can be produced on large scale. In this study, the nanoparticles were supplied in the form of powder by the manufacturer. The nanofluids were prepared by suspension of the nanoparticles in the base fluid using the ultrasonic device. A field emission scanning electron microscope (FESEM) is microscope that works with electrons (particles with a negative charge) instead of light. These electrons are liberated by a field emission source. Fig. 4 presents the FESEM for the SiC types of nanoparticles.

2.4. Thermo-physical properties of nanofluids

Fig. 5 shows the thermo-physical properties of the nanofluids at different temperatures. The thermo-physical properties of nanofluids such as thermal conductivity, density and viscosity were determined. The thermo-physical properties of nanofluids were required to determine the heat transfer coefficient of the nanofluids. A KD2-Pro thermal properties analyzer (made by Decagon, USA) was used to measure the thermal conductivity of nanofluids. DH-300L Leading Factory Liquid Density Tester (made by Dongguan Hongtuo Instrument Co., Ltd.) was used to measure the density of nanofluid. A Brookfield (LVDV III ultra-programmable) viscometer was used in this experiment to measure the viscosity.

As observed from Fig. 5 the thermal conductivity increased with the increase of volume concentrations and temperature and follows the behavior of the base fluid (water) thermal conductivity. All thermal conductivity of the nanofluids at this concentration range was found to be higher than its base fluid (water). The observation of this trend seems to be related to the Brownian motion. At