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Mathematical and experimental evaluation of thermal and electrical efficiency of PV/T collector using different water based nano-fluids

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A B S T R A C T

The high temperature of PV modules is one of the major factors that affect the PV system performance. The PV/T collector is proposed mainly to recover the heat of the high PV module temperature using conventional working fluids (water/air). Nanofluids (NFs) would help enhance the heat transfer/heat removal. The effect of NFs on enhancing the electrical/thermal efficiency of the PV/T collector besides the fluid's outlet temperature were investigate theoretically and experimentally. Fluent simulation tool together with energy balance equations were used. Three rounds of analysis were performed. Firstly, the optimal design of "sheet and tube" thermal absorber was determined using water as the base fluid. Secondly, the PV/T performance aspects using three types of NFs (CuO, SiO_2, and ZnO) and water, were compared. Thirdly, the life cycle cost analysis/profit gain were applied to examine the feasibility of the grid connected PV/T-NF. The results showed that the optimal design of the PV/T thermal absorber requires 11 rectangular tubes per module, and the optimal rectangular tube dimensions are 24 mm (width) and 15 mm (depth). The results also revealed that the NF-SiO_2 showed outstanding enhancement compared to other types of NFs and water. In addition, the results revealed that using NF- SiO_2 in the PV/T collector reduced the PV module temperature from 65 °C to 45 °C and increased the outlet temperature from 35 °C to 44 °C, leading to an electrical and thermal efficiency enhancement of 12.70% and 5.76% respectively at a solar irradiance of 1000 W/m^2. Payback analysis and profit gain of grid connected PV/T-NF (SiO_2) system, grid connected PV/T- water system, and (grid connected PV + solar thermal) system were found (8 yrs, 10218.137 $; 11 yrs, 5518.518 $; 15 yrs, 3816.873 $), respectively. This indicated that the grid connected PV/T-NF (SiO_2) system is economically feasible compared to the other systems despite the additional initial cost of the expensive NFs and the customized heat exchanger.

1. Introduction

Problems such as low PV efficiency, architectural uniformity, and limited space on a roof to install separate systems led to the idea of combining PV/T into one complete system Sok [1] & Zondag [2]. A PV/T system has a high total energy conversion efficiency; it converts solar energy into electrical and thermal energy by removing the heat from the PV module temperature using working fluids Al-Shamani [3]. The performance and the economic competitiveness of the PV/T collector or any other solar collectors depend upon various design parameters such as absorber heat exchanger materials [4–6], absorber design configuration [7], PV/T collector length [8], PV/T collector depth [9], number of collectors [10], sun tracking system [11], PV module type [12], glazed and unglazed collector [13], concentrated solar irradiance [14], tube

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Nomenclature

A_c	Collector area (m^2)
C_p	Specific heat of water (J/kg K)
FF	Fill factor of PV module
F	Fin efficiency
F'	Collector efficiency factor
F''	Collector flow factor
F_R	Collector heat removal factor
I_t	Solar irradiance (W/m^2)
H	Convective heat transfer coefficient (W/m^2 K)
h_r	Radiative heat transfer coefficient (W/m^2 K)
W	Width of absorber tube
τ	Transmissivity
κ	Boltzmann constant, $1.3807*10^{-23}$ J/K
k	Thermal conductivity (W/m K)
L	Length of collector (m)
$\dot{m}$	Mass flow rate (kg/s)
Q_u	Actual useful heat gain (W)
S	Absorbed solar energy (W)
T_p	Photovoltaic collector temperature (°C)
T_a	Ambient temperature (°C)
T_i	Inlet fluid temperature (°C)
T_o	Outlet fluid temperature (°C)
U_L	Overall collector heat loss coefficient (W/m^2 K)
D	Height of absorber tube
α	Absorptivity
I, V	Current (A), Voltage (V)

spacing to tube diameter (W/D) ratio [15], and working fluid types such as air/water [16].

Over the past decades, numerous numerical and experimental studies investigated the performance of PV/T systems and solar thermal collectors using water as the base fluid for heat removal. It is proven that temperature fluctuations while using water as a base fluid are significantly less than those used air as a base fluid in PV/T and other solar collectors [12]. Despite that, heat removal is still limited due to conventional thermo-physical properties of water. Moreover, conduction/convection/radiation losses to the surroundings in PV/T and other solar thermal collectors, required efficient heat transfer approaches to minimize these losses [17].

Nanofluids (NFs) are a mixture of liquid-based fluids and nanoparticles [18]. Nanoparticles would improve thermo-physical properties of the conventional liquid fluids such as thermal conductivity, viscosity, and convective heat transfer coefficient [19]. Therefore, NFs are used to replace conventional fluids in order to improve the heat transfer in PV/T systems [20–31]. A technical summary of the overall performance enhancement of PV/T and solar other thermal collectors using NFs is provided in Table 1.

Thermal absorber is one of the main functional elements of a PV/T collector; it could be made using many manufacturing approaches. The most adopted configuration is "sheet and tube" [42] due to its simple manufacturing process and low thickness requirements. So far, the parametric design analysis of the "sheet and tube" thermal absorber of the PV/T collector is not presented in detail in the literature. Therefore, parametric design of "sheet and tube" thermal absorber, to determine the minimum number of absorber tubes, minimum tube dimensions, and minimum mass flow rate that enable maximum PV/T temperature reduction using water as a working fluid is accomplished in this study.

Then, mathematical and experimental evaluations were conducted to evaluate the performance enhancement of the PV/T system under different water based nanofluids (CuO, SiO_2, and ZnO). The theoretical analysis was performed using the CFD-ANSYS and energy balance equations. Then, outdoor experimental test was conducted under tropical climatic conditions to validate the theoretical results.

2. Materials and method

2.1. Research design

To achieve the objectives of this study, different approaches of analysis were used as follows:

1. CFD ANSYS simulation tool, together with energy balance equations.
2. Outdoor test under tropical climatic conditions to evaluate the experimental performance of PV/T-water and PV/T-NF.
3. Life cycle cost analysis (LCCA).

Fig. 1 illustrates the block diagram of the work's evolution methodology. To accomplish the objectives, the research activities performed are illustrated in the block diagram shown in Fig. 2.

2.2. Materials

2.2.1. Base fluid and nanofluids

The NF is a special type of fluid that has a suspension of nanoparticles in the base fluid. The two-step method was used to prepare the NFs. Firstly; the nanoparticles were prepared in a powder form by physical or chemical methods, such as grinding laser ablation, sol-gel processing, etc. Secondly, the nanoparticles was suspended in a base fluid [43]. Water was used as the base fluid, and CuO, SiO_2, and ZnO NFs were implemented in this work.

The NFs were prepared by the suspension of the nanoparticles in the base fluid using the ultrasonic device. A field emission scanning electron microscope (FESEM) is a microscope that works with electrons (particles with a negative charge) instead of light. These electrons are liberated by a field emission source. After the preparation of NFs, experimental thermo-physical properties were measured. Table 2 shows the thermo-physical properties of water and CuO, ZnO, and SiO_2 NFs with a concentration ratio of 1%wt. at different temperatures. The thermo-physical properties of NFs, such as thermal conductivity, density, and viscosity, were determined. The thermo-physical properties of NFs are required to determine the heat transfer coefficient of the NFs. A KD2-Pro Thermal Properties Analyzer (Decagon, USA) was used to measure the thermal conductivity of NFs. DH-300L Leading Factory Liquid Density Tester (Dongguan Hongtuo Instrument Co., Ltd) was used to measure the density of NFs. A Brookfield (LVDV III ultra-programmable) viscometer was used in the experiment to measure the viscosity.

2.2.2. Experimental setup of the PV/T system

The PV/T system is a closed-loop system wherein the coolant liquid that enters the tubes is continuously heated. The used PV/T collector and the design of the thermal absorber are shown in Fig. 3 (a and b). The specifications of the PV module and the PV/T collector, with the assumed working conditions, are presented in