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Numerical and experimental investigation on the performance of a photovoltaic thermal collector with parallel plate flow channel under different operating conditions in Malaysia

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ABSTRACT

Solar energy is universally accepted as the most potential alternative power source due to its inexhaustible availability, diverse conversion technology and environmental friendly nature. Hybrid photovoltaic-thermal (PV/T) system is an optimized solar energy system that produces electricity and thermal energy simultaneously from the same physical profile. The basic problem of the hybrid collector is the removal and transfer of heat in an efficient way. In this article, PV/T system with a novel design of thermal collector excluding the absorber plate has been introduced to resolve the above mentioned problem. A parallel plate thermal collector without absorber plate has been attached directly to the PV module backside by means of thermal paste only and the performance of the PV/T is evaluated numerically and validated by experimental data for different operating conditions. A 3D numerical analysis of the PV/T system has been performed using finite element method (FEM) based software COMSOL Multiphysics®. The outdoor experimental investigation has been done under the typical climatic condition of Malaysia. Elevation head of water has been employed to ensure passive cooling of PV module. The numerical simulation results are found in well agreement with those of experimental measurements. Thermal performance of PV/T without absorber plate is found almost as good as that with absorber plate. The numerical and experimental values for maximum overall efficiency of the PV/T system was found 84.4% and 80%, respectively under the irradiation level at 1000 W/m^2 with both inlet and ambient temperatures being 34 °C. The developed simulation model can be extended for other designs of thermal collector using different materials.

1. Introduction

The major share of the energy demand is globally met by conventional fossil fuels which are depleting rapidly day by day (Asif and Muneer, 2007). The global energy consumption trend predicts that the contribution of fossil fuels (oil, gas, coal) in the energy mix in 2040 will be 78% despite of the faster growing trend of the non-fossil fuels (renewable and nuclear energy) (Conti et al., 2016). Moreover, fossil fuels emit greenhouse gases (GHG) which are very harmful to the environment. Therefore, replacing the fossil fuels with renewable sources in power generation is the future challenge to ensure sustainable and secured power supply as well as mitigate the environmental issues (Hasanuzzaman et al., 2011). Among the renewable energy resources, solar energy is considered the most promising and highly reliable clean energy technology. Solar energy may be harnessed and utilized in two forms, such as heat and electricity. Solar thermal energy is collected by solar thermal collectors and electrical energy is produced by photovoltaic (PV) modules. However, the demand for heat and electricity are often supplementary. Hybrid photovoltaic thermal (PV/T) system is a well-engineered solar co-generation system combining PV module and solar thermal collector (STC) in one physical profile to provide both electricity and heat simultaneously. The initiatory drive behind PV/T technology was that PV modules were found to absorb substantial amount of solar radiation which produce undesirable heat in the cells.

The commercially available solar cells are reported to have efficiencies in the range of only 6–16% at 25 °C temperature which again drops at rate of 0.4–0.65% per degree increase temperature

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Nomenclature

A_c	PV cell area (m^2)
A_{fc}	cross-sectional area of the inlet flow channel (m^2)
C_p	specific heat capacity at constant pressure ($J\,kg^{-1}\,K^{-1}$)
C_{pw}	specific heat capacity of water ($J\,kg^{-1}\,K^{-1}$)
D_i	inner diameter (m)
E_c	total solar energy into the cell (W)
E_{el}	electrical energy (W)
E_{th}	thermal energy extracted by water (W)
$\mathbf{F}$	volume force (N)
h_c	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_T	conductive heat transfer coefficient from solar cell to water through tedlar ($W\,m^{-2}\,K^{-1}$)
$\mathbf{I}$	moment of inertia ($kg{\cdot}m^2$)
I_{mp}	maximum power point current (A)
k	thermal conductivity of the material ($W\,m^{-1}\,K^{-1}$)
k_w	thermal conductivity of water ($W\,m^{-1}\,K^{-1}$)
m	mass flow rate ($kg\,s^{-1}$)
$\mathbf{n}$	surface normal
P	pressure (Pa)
p_c	packing factor
Q	total heat generation (W)
Q_c	convective heat loss ($W\,m^{-2}$)
q	inward heat flux
R	solar irradiance (W/m^2)
Re	Reynolds number
t	time (s)
T_{amb}	ambient temperature (°C/K)
T_b	temperature of back surface (°C/K)
T_c	temperature of PV cell (°C/K)
T_{in}	water inlet temperature (°C/K)
T_{out}	water outlet temperature (°C/K)
T_{ref}	reference temperature (°C/K)
$\mathbf{u}$	velocity field (m/s)
U_o	inlet water velocity (m/s)
V	wind velocity (m/s)
V_{mp}	maximum power point voltage (V)

Greek symbols

∇	vector differential operator
β	temperature coefficient at reference cell temperature
μ	dynamic viscosity of the fluid ($m^2\,s^{-1}$)
ν	kinematic viscosity of the fluid ($m^2\,s^{-1}$)
ρ	density of the fluid ($kg\,m^{-3}$)
η_{ref}	PV cell electrical efficiency at reference temperature
η_{th}	thermal efficiency
η_{el}	electrical efficiency
η_{tol}	total PV/T system efficiency
τ_g	glass emissivity
α_c	absorptivity of PV cell
α_T	absorptivity of tedlar

(Hasan et al., 2010). The unwanted heat thus generated deteriorates the efficiency of the PV cells which may be improved to some extent by removing the heat from the module. The waste heat thus removed to cool the PV module may further be utilized in useful heating applications which lead to the hybrid PV/T technology offering a better way of utilizing solar energy with higher overall efficiency. The foremost advantage of PV/T systems is that they produce twofold yields with a little extra cost and half of the space. Moreover, it is an efficient and flexible technology which can be used for both heating and cooling purpose (Kumar et al., 2015).

The inception of PV/T research was commenced due to the works of Wolf (1976) and Kern and Russell (1978) followed by the studies of Hendrie (1979), Florschuetz (1979) and Cox and Raghuraman (1985) on design and performance of air and water cooled PV/T systems. However, engrossment on research to improve the efficiency of PV/T systems acquired the due pace in 2000 onwards. He et al. (2006) experimented on a water based PV/T collector with a polycrystalline PV module attached with flat box type aluminum alloy collector. Authors found that daily thermal efficiency could reach 40% with better energy saving efficiency over conventional thermosiphon collector system. Robles-Ocampo et al. (2007) experimented on a hybrid system model with bifacial PV module and found higher efficiency for this hybrid system compared with conventional system. Tiwari and Sodha (2007) experimented on four different configurations of hybrid PV/T air heater. The configurations numerically modeled and tested were glazed and unglazed PV/T with or without tedlar out of which glazed PV/T collector without tedlar turned out to perform the best. Erdil et al. (2008) constructed two parallel connected PV/T in which they attached a 4-mm-thick glass sheet, 0.005 mm over the PV module making a cavity for water flow to take the heat away for household thermal applications. Authors reported a daily generation of about 2.8 kW h thermal energy from the PV/T system. Bakker et al. (2002) designed and fabricated a model of a dual flow PV/T combi-panel and also developed a numerical simulation model to predict the thermal efficiency of the prototype. Although the authors reported very good thermal performance of the dual flow scheme, it makes the system very heavy and infeasible for large scale applications. Othman et al. (2013) experimented on a PV/T collector using water and air as heat transfer fluid. Authors analyzed three designs: double pass PV/T collector with fins, and parabolic concentrator (CPC), and with V-groove absorber. Results showed that the collector with fins performed poorly than that one with CPC and fins. Tonui and Tripanagnostopoulos (2007) made use of a thin flat metal sheet suspended in the middle of an air channel of a PV/T air collector or attached on its back wall as fin. Authors developed a theoretical model of the scheme and validated it by experimentation and reported improved efficiency of the PV/T air system through this modification. Tonui and Tripanagnostopoulos (2008) developed a mathematical model of a flat plate collector with glazed and unglazed based on natural ventilation and investigated the effect of parameters like mass flow rate, ambient temperature, and tilt angle on PV/T performance. Authors found that thermal efficiency decreases with increasing ambient air temperature and increases with increasing tilt angle for a particular irradiation level. Chandrasekar et al. (2013) investigated the thermal and electrical performance of a flat plate PV module cooled by cotton wick structure attached at back side of the module which was soaked by water and two different nanofluids of CuO/water and Al_2O_3/water. Authors reported a reduction in cell temperature by 20 °C and an increase the electrical efficiency by 1.4% in the outdoor operating conditions. Rahman et al. (2015) experimentally investigated the effect cooling water flow rate along with some other parameters on the performance of PV module and found considerable reduction in module temperature. Teo et al. (2012) carried out experimental investigation on PV/T air collector with and without active cooling. Authors found high module temperature with low cell efficiency of 8–9% without active cooling; on the other hand, with active cooling the module temperature was found to reduce appreciably with an increased cell efficiency of 12–14%. Also authors developed a heat