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Numerical investigation on the effect of different parameters in enhancing heat transfer performance of photovoltaic thermal systems

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ABSTRACT

Photovoltaic thermal (PV/T) collectors that supply both electricity and heat are growingly becoming popular in household and other applications. However, efficient heat removal from backside of PV module is still a challenge that hampers its electrical as well as thermal performance. In the present research, an absorber-plate less thermal collector has been introduced and mathematical model of such a PV/T system has been developed, which is employed in COMSOL Multiphysics® software to simulate the heat transfer phenomenon in the system. Effect of different flow parameters on heat transfer and PV/T performance is thus studied numerically in the developed simulation model. Also, the effect of irradiation level and depth of the flow channel has been examined on the thermal as well as electrical performance of the module. Results reveal that PV/T electrical and thermal efficiency increase with both of Reynolds and Prandtl number. Heat transfer rate is observed to increase as high as 25.5% with increasing Reynolds number. A maximum reduction in cell temperature of 10.2 °C is obtained by increasing the channel depth. Elimination of absorber plate from thermal collector simplified the design reducing its weight and cost as well.

1. Introduction

The worldwide concern for developing sustainable and environmental friendly energy technologies that are feasible for commercial as well as residential applications is growing day by day due to the issues like scarcity of mineral sources of fuel, global warming and other pertinent issues [1,2]. Solar energy is the most potential and promising source of renewable energy that can be harvested in two forms, viz. solar thermal and electricity. However, electricity production by PV technology suffers from poor energy conversion efficiency. It has been reported that only 15% of solar irradiation is converted into electricity; the rest being reflected and converted into heat out of which only 60% may be collected by a solar collector by PV/T collector [3,4]. Moreover, traditional silicon solar cells suffer from a drop-in efficiency with increase in cell temperature. An optimized solution is to extract the excess heat from the module and make use in thermal applications. Photovoltaic thermal (PV/T) offers this solution providing both electricity and heat from the same physical profile. A significant number of numerical and experimental studies on PV/T are available in the literature [5–8]. But, the challenge with this combination technology is to improve both of the electrical and thermal efficiency. Researchers have pointed out two major ways to enhance the performance, viz., reducing the operating temperature of the PV cell [9,10] and increasing the packing factor [11]. However, the basic problem with PV/T system is the effectual removal of heat from the module and transfer it to user end for making efficient utilization. Effective removal and transfer of heat depend on the deft design of thermal collector as well as its well integration with the PV module.

A numerical model of a PV/T-water system was established by Chow et al. [12] whereby model's accuracy was tested against the calculated data. Authors investigated collector performance by temperature reduction analysis and extended the study to analyze the system efficiency both in the summer and winter environment in China. Eck et al. [13] developed a two-dimensional and also a three-dimensional FEM model portraying the non-uniform solar heat distribution by ray tracing simulations, which showed a good

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Nomenclature

A_c	Area of cell (m^2)
A_f	Flow channel cross-sectional area (assuming unit depth) (m^2)
C_p	Specific heat at constant pressure (J/kg.K)
d	Depth of flow channel (m)
D_h	Hydraulic diameter (m)
E	Rate of energy transfer (W)
h	Heat transfer coefficient (W/m^2K)
k	Thermal conductivity of fluid (W/m.K)
L	Length of the duct (m)
Nu	Nusselt number
P	Pressure
P_e	Perimeter (m)
P_c	Packing factor
Pr	Prandtl number
$\dot{Q}$	Rate of heat generation (W)
R	Solar irradiance (W/m^2)
Re	Reynolds number
T	Temperature (°C)
u,v	Fluid velocity (m/s)
U_o	Inlet water flow velocity (m/s)

Greek symbols

δ	Thickness (mm)
μ	Dynamic viscosity (m^2/s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
η_{th}	Thermal efficiency
η_{pv}	Electrical efficiency
η_{tol}	Total PV/T panel efficiency
τ	Emissivity
α	Absorptivity

Subscripts

amb	Ambient
c	Cell
conv	Convection
el	Electrical
duc	Duct
f	Fluid
g	Glass
in	Influx, inlet
mod	PV module
out	Outflux, outlet
ref	Reference
s	Sky
S	Surface
td	Tedlar
th	Thermal
tol	Total
w	Water

agreement with available measurements. Recently, Nahar et al. [14] developed a 3D mathematical model for PV/T with a pancake shaped flow channel and numerically simulated it in COMSOL Multiphysics® software to analyze PV/T performance.

Dubey et al. [15] experimented with four different PV configurations: glass to glass PV module with duct and without duct, glass to tedlar PV module with duct and without duct. Results showed that the electrical efficiency as well as outlet air temperature of glass to glass configuration with duct was the highest among the all four configurations. Dubey and Tiwari [11] had developed a thermal model of PV/T (glass to glass) solar water heater where the results showed a significant rise in instantaneous efficiency with increasing in glazing area. Thermal performance of single-pass and double-pass PV/T air systems was investigated by Sopian et al. [16] wherein double-pass configuration shown better performance than the typical single-pass configuration. Yang et al. [17] used functionally graded material (FGM) attached with copper pipe of the thermal collector by thermal paste. The authors reported to increase the electrical efficiency by 2% and achieved an overall efficiency of 71%. Zondag [18] introduced a model of PV/T water collector and experimented the system with varying sizes. The electrical and thermal efficiency attained were 6.7 and 33%, respectively. Cadaflach [19] extended the work of Duffie and Beckman [20] and developed a simulation model of flat-plate PV/T. The one-dimensional model was tested by monitoring single and doubles glazed collectors in steady state. Chow [9] developed a transport delay flow model for a single-glazed flat plate PV/T water collector by using finite difference method. Author analyzed the energy flow through different components of the collector in order to realize the instantaneous yields. Numerical modeling of a photovoltaic−thermosiphon system and subsequent experimental analysis was performed by Chow et al. [21]. Authors found it feasible for domestic applications only.

Literature study reveals that two forms of hybrid PV/T system are considered so far: tube-in-plate [9,18,22,23] and parallel plate configuration [22,24,25]. In this research, a parallel plate channel excluding the absorber sheet has been considered for PV/T-water system. This exclusion makes the design simple and ensures a well integration with the PV module. A mathematical model of PV/T system has been developed and the model is solved in COMSOL Multiphysics®. The effect of Reynolds number and Prandtl number on heat transfer and PV/T system performance has been analyzed. Also, the effects of irradiation and flow channel depth are observed.

The subsequent sections of the article are organized in the following manner: The step by step procedure of developing the mathematical model of the PV/T system has been detailed in Section 2 including the basic governing equation, assumptions set for developing the model, formulation of layer by layer partial differential equations, setting the boundary conditions and mesh generation process; Section 3 contains the model validation and numerical outcomes of model such as effect of Reynold number and Prandtl number on PV/T parameters, effect of cell temperature and effect of irradiation on system performance; Section 4 gives a summary of different aspects, especially the outcomes of present research work.

2. Mathematical modeling for PV/T system

A detailed layer-by-layer mathematical model for the proposed PV/T system has been developed and numerical simulation of the model has been accomplished in COMSOL Multiphysics®. The parallel-plate thermal collector is directly attached to the backside of a monocrystalline PV panel without any intermediate absorber plate using thermal conductive adhesive. Fig. 1 shows different layers of the PV/T system. Analyses have been carried out with three different flow channel depths of 0.02, 0.015, 0.010 m. Data analysis has been carried out in Tecplot 10, a powerful, simple to use tool for visualizing technical data with XY Plots, -2D Plots, -3D