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Analysis of a vacuum-based photovoltaic thermal collector

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Abstract

In this study, a new design of photovoltaic thermal (PV/T) collector is proposed. This design uses a vacuum layer above the silicon wafer and not exists in the traditional PV/T collector. This layer is used to decrease the heat loss from the top surface of the PV/T collector. The analysis is conducted using a 3D thermal modeling. The new collector design with the vacuum layer achieved a 26.6% increase in the thermal power while keeping the electrical the same at Reynolds number of 50 and solar radiation of 1000 W/m^2. In addition, the degradation of the vacuum pressure slightly influence the thermal performance while increasing the vacuum pressure from 0.01 Pa to 10 Pa. While further increase in the vacuum pressure from 10 Pa to 1.013×10^5 Pa substantially decreases the gained thermal power with insignificant increase in the electrical power.

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Keywords: Vacuum-based photovoltaic thermal collector; Vacuum pressure; Thermal energy; CFD; Minichannel

1. Introduction

In preference to the major source of energy to our planet, solar energy is the promising source to cover the growing needs. Solar energy is the most plentiful and eco-friendly, renewable form of energy [1] which can be collected directly into electrical or thermal energy form by different technologies. In general, the photovoltaic (PV) solar cells are used to collect the incoming solar radiation and convert it into electricity. Meanwhile, the solar thermal collectors commonly convert the solar radiation into thermal energy. Certainly, the Si-based PV products

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Nomenclature

G	Solar radiation, [W/m^2]
A	Area, [m^2]
k	Thermal conductivity, [W/m K]
P	Pressure, [Pa]
q	Heat generation, [W/m^3]
T	Temperature, [K]
U	Velocity component in x direction, [m/s]
V	Velocity component in y direction, [m/s]
Cp	Specific heat capacity [J/kg K]
W	Velocity component in z direction, [m/s]

Greek symbols

μ	Fluid viscosity [Pa s]
ρ	Density [kg/m^3]
α	Solar radiation absorptivity
τ	Transmittivity
η	solar cell electrical efficiency

Abbreviations

PV/T	Photovoltaic thermal
VPV/T	Vacuum based photovoltaic thermal

dominate the solar cells market in consequence of their reasonable cost. However, the electrical performance of PV declines linearly with any increase in the cell temperature [2]. The Si-based PV efficiency drops about 0.4% to 0.6% per 1 K temperature rise [3]. Recently, solar radiation can be converted to both thermal and electrical energy in photovoltaic thermal (PV/T) systems [4]. Whilst PV/T technology has many potentials for a broad application as it is capable to generate electrical and thermal energy simultaneously with satisfactory overall performances. Moreover, the PV/T has the benefit of a limited footprint in contrast with the two apart PV systems and thermal collectors. Furthermore, the concentrated PV/T (CPV/T) arrangements offers additional footprint reduction of the PV/T. At the CPV/T systems, the concentration optics are used to focus and direct the incoming solar radiation into lower are of the PV receiver compared to non-concentrated systems. The CPV/T has the benefits of low cost and improved thermal and electrical performance. However, the main challenge of the CPV/T systems is the high rise of the cell temperature hence a more powerful thermal management system is needed. Also, the heat absorbed by the absorber plate needs to be transferred to working fluids rapidly to prevent system overheating [5].

Generally, the PV/T collectors is one of the wide spreading research subjects over the last three decades. The liquid or gas media were usually employed in the PV/T for thermal management of the PV cells [6]. Air and water glass covered collectors were studied in the beginning [7], but uncovered PV/T collectors rapidly considered by many researchers [7,8]. Recently a wide range of working fluids were studied, such as ethylene glycol [9], oil [10], hybrid ethylene glycol/phase change material (PCM) [11], hybrid water and air [12], and nanofluids [13]. The broad efforts in the literature showed a considerable enhancement in the performance of the PV/T in terms of electrical and thermal efficiencies [7]. Though, one can say that the PV/T is not a mature technology yet. As, the trend for progress in the PV/T is still strictly constrained due to a variety of inherent practical difficulties. Originally, the fluid-based arrangements still suffer from the temperature maldistribution and the temperature rise between the inlet and outlet. Hence, the dropping solar efficiency usually happens with the difference of the coolant temperature over the working time [2]. Furthermore, the high coolant temperature operation leads to a low heat dissipation effectiveness consequently a low thermal efficiency is expected [14]. Also, the deployment of PV/T systems is still restricted by the instability and sporadic nature territorial conditions. Furthermore, the broad electric and thermal energy storage technologies are still not adequate to match the market requirement [15]. Hence, additional comprehensive investigations have to be done to cover the research gap regarding the PV/T by manipulating the key factors such as terrestrial parameters (ambient temperature, wind speed, etc.).

In the PV/T systems, a heat sink containing water stream is attached to the backside of the PV to absorb the thermal energy generated in the photovoltaic module. This allows us to avoid excessive heating of the solar cells and to reach undesirable cell surface temperatures. It is necessary to enhance the thermal and electrical efficiencies of the PV/T system. This can be attained by reducing the thermal heat loss from the top surface of the PV/T system. This idea is applied evacuated plate solar thermal collectors. However, the evacuated plate PV/T collector cannot be found in the literature. In most of the recent investigations, the conventional PV module is attached to a thermal absorber for heat recovery. At windy weather conditions with low ambient temperature, the heat loss from the top surface of the PV increases. Hence, a huge thermal energy can be wasted to the atmosphere. Therefore, developing an efficient design for the PV/T module with high thermal and electrical energy gain is of great importance. This allows us to obtain high thermal energy for space heating in domestic and industrial sectors along with electrical energy gain. In most recent PV/T investigations, the backside of the thermal absorbers was presumed to be thermally insulated for higher thermal energy gain. However, due to the transparency requirements of the top PV/T surface, no conventional thermal insulation can be utilized.

Therefore, the current study applies the use of vacuum layer above the silicon wafer in the PV/T collectors to decrease the heat loss from the top surface of the PV/T. A 3D thermal analysis is developed to compare the performance of the PV/T system with and without vacuum layer. Both designs were cooled using a serpentine flat design thermal absorber. Compassion is executed at the same conditions. Finally, the effect of vacuum layer pressure on the thermal and electrical energy gain is estimated.

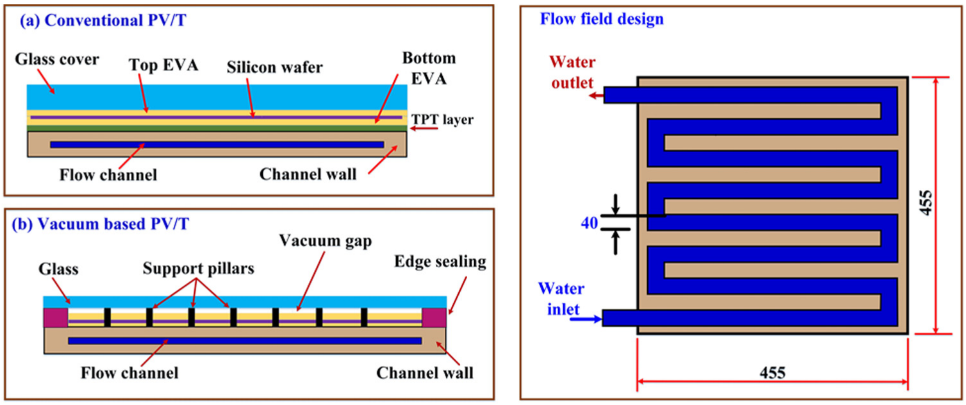

Fig. 1. Detailed structure of the conventional (a) conventional PV/T system (top Left) and (b) the new VPV/T module (bottom left) and the details of the flow field (Right).

2. Theoretical analysis

In this study, the traditional design of the PV/T system and the PV/T system with vacuum layer, called (VPV/T), were numerically simulated and compared. The details of these designs were depicted in Fig. 1a and b, respectively. The VPV/T system has a vacuum layer with thickness of 0.3 mm above the silicon wafer to decrease the heat loss from the top surface of the silicon wafer to the atmosphere. In both collectors, a serpentine flow field is used for the thermal management of the PV. In the traditional PV/T system in Fig. 1a, it consists of a glass, top EVA, silicon, bottom EVA, and finally Tedlar layers with 3 mm, 0.5 mm, 0.2 mm, 0.5 mm, 0.3 mm thicknesses respectively. The thermal absorber is designed from aluminum with 1 mm thickness. The design of the thermal absorber is used as the same in both collectors. However, in the VPV/T collector, the thicknesses of the glass, vacuum gap, top EVA, silicon wafer, bottom EVA are 3 mm, 0.3 mm, 0.5 mm, 0.2 mm, 0.2 mm, respectively and has no Tedlar. This design has a lower thickness of lower EVA and removed the Tedlar to enhance the heat dissipation to the water in the thermal absorber as concluded in [16]. To sustain the vacuum gap, an array of circular support pillars spaced at 50 mm are used as recommended by Arya et al. [17]. The active PV module area was 455 mm × 455 mm for both collectors. The energy equation for the solid layers is represented as follows [18]:

$$\rho c_p \left(\frac{\partial T}{\partial \mathrm{t}}\right) = k_i \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_i \tag{1}$$

The value of q_i occurs in glass cover, top EVA, and the silicon wafer and estimated using correlations in [16]. The electrical efficiency depends on the cell operating temperature as follows [19]:

$$\eta_{sc} = \eta_{ref}(1 - \beta_{ref}(T_{sc} - T_{ref})) \tag{2}$$

where: η_{ref} is 20% at T_{ref} of 25 °C. And T_{sc} is the solar cell operating temperature. The value of β_{ref} is 0.0045 K^{-1} for polycrystalline silicon. The flow governing equations in the mini-scale serpentine thermal heat absorber at steady, laminar flow, and incompressible can be written as follows:

Continuity equation:

$$\frac{\partial \rho U}{\partial x} + \frac{\partial \rho V}{\partial y} + \frac{\partial \rho W}{\partial z} = 0 \tag{3}$$

Momentum equations in x, y, and z directions:

$$U\frac{\partial \rho U}{\partial x} + V\frac{\partial \rho U}{\partial y} + W\frac{\partial \rho U}{\partial z} = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}\right) \tag{4}$$

$$U\frac{\partial \rho V}{\partial x} + V\frac{\partial \rho V}{\partial y} + W\frac{\partial \rho V}{\partial z} = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right) \tag{5}$$

$$U\frac{\partial \rho W}{\partial x} + V\frac{\partial \rho W}{\partial y} + W\frac{\partial \rho W}{\partial z} = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2}\right) \tag{6}$$

Energy equation:

The energy equation for the cooling water in the thermal absorber is expressed as follows:

$$U\frac{\partial \rho C_p T}{\partial x} + V\frac{\partial \rho C_p T}{\partial y} + W\frac{\partial \rho C_p T}{\partial z} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{7}$$

Surface to surface (S2S) model is used to consider the heat transfer process in the vacuum layer via thermal radiation. The S2S model governing equations and limitations exists in the ANSYS theory guide ("ANSYS FLUENT Theory Guide", [20]). For the boundary conditions, a uniform water velocity with a temperature of 30 °C is applied at the inlet of the thermal absorber for both collectors. The simulation is conducted at solar radiation of 1000 W/m^2. The values of flow Reynolds number varied from 10 to 150. Standard atmospheric pressure is defined at the channel outlet. Mixed convection and radiation boundary condition is justified at the top of the glass layer. The convection heat transfer coefficient due to the wind effect is 9.89 W/m^2 K as for 1 m/s wind speed with an atmospheric temperature of 30 °C. Thermal coupled boundary conditions are at interfaces between every two consequent layers. And no slip B.C is applied at the interface between the water and the channel wall. Adiabatic backsides and computational domain sides are applied for both collectors. The CFD model is applied to simulate the experimental conditions of El et al. [21] at the conditions depicted in Table 1. This step is used to compare the PV output electrical power with the experimental results in [21] for the traditional PV collector. In Fig. 2, it is noticed that the model is accurately estimate the electrical power with maximum relative error of 7.9%.

Table 1. Weather conditions and flow conditions used through the validation steps as measured in [21].

	Simulated hours for validation				
	8:00	10:00	12:00	14:00	16:00
Solar radiation, W/m^2	317.0	531.7	655.2	558.3	257.7
Air inlet velocity, m/s	2.7	1.4	1.7	1.8	1.8
Ambient temperature, °C	29.1	31.9	38.1	41.1	40.1
Air inlet temperature, °C	32.0	34.8	42.2	42.1	40.9

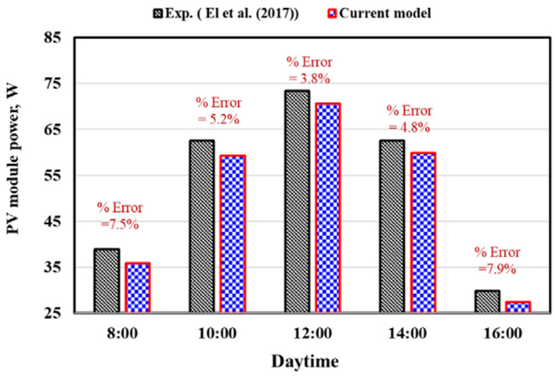

Fig. 2. Comparison of the present estimated PV module power with the measured PV module power the experiment of El et al. [21].

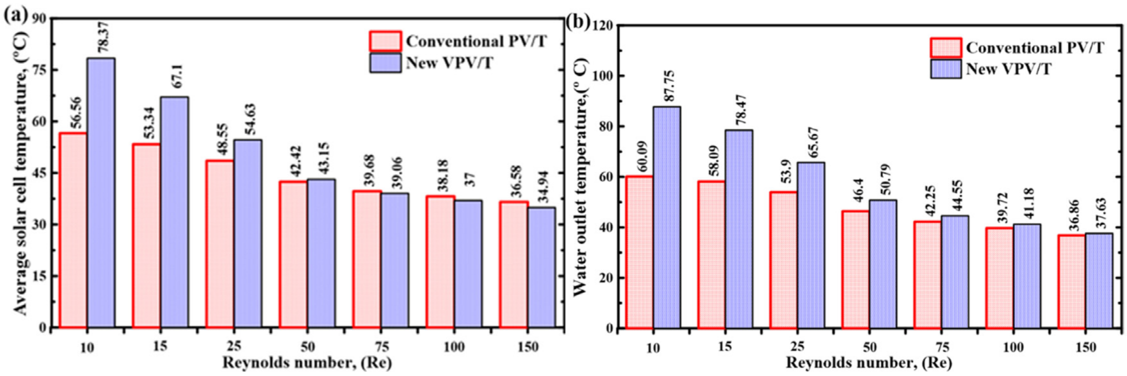

Fig. 3. Variation of (a) solar cell average temperature and (b) water outlet temperature.

3. Results and discussion

The influence of the average solar cell temperature and cooling outlet temperature with Re number for both PV/T and VPV/T collectors were depicted in Fig. 3a and b, respectively. Increasing Re substantially decreases the average PV temperature and the water outlet temperatures. However, the PV temperature is higher in the VPV/T compared to PV/T collector. But at Re = 50, the PV temperature for both collectors are nearly the same. While the water exit temperature in the VPV/T collector still higher than PV/T collector at the same Re number. For instance, the outlet cooling water temperature is 50.5 °C and 46 °C for VPV/T and PV/T collectors at Re = 50. The higher outlet temperature, the higher thermal energy gain. Hence, the electrical and thermal power gain variation with Re number was illustrated in Fig. 4a and b, respectively. Increasing Re enhances both the thermal and electrical thermal power. However, at Re = 50, the electrical power for both collectors are nearly the same. But the thermal power is enhanced by 26.3% while using the VPV/T collector. These findings clarify the advantage of using the VPV/T system with the ideal selection of the flow cooling conditions.

At Re of 50, solar radiation of 1000 W/m^2 and wind speed of 2 m/s, the temperature contours on the top glass cover is depicted in Fig. 4c and d for the PV/T and VPV/T collectors, respectively. The top glass temperature of the PV/T is higher than in the VPV/T collector. This explains the higher heat loss from the top cover. Further, the pillars and edge sealing effect act as a thermal bridge in the VPV/T collector. This thermal bridge can be decreased by using low thermal conductivity edge sealing composite and larger module area [22]. The effect of vacuum pressure on the maximum cell temperature and the top glass cover temperature of the VPV/T system is depicted in Fig. 5. Increasing the pressure from 0.01 to 10 Pa marginally changes the maximum cell temperature. And additional vacuum pressure increases lead to a significant decrease the top glass cover.

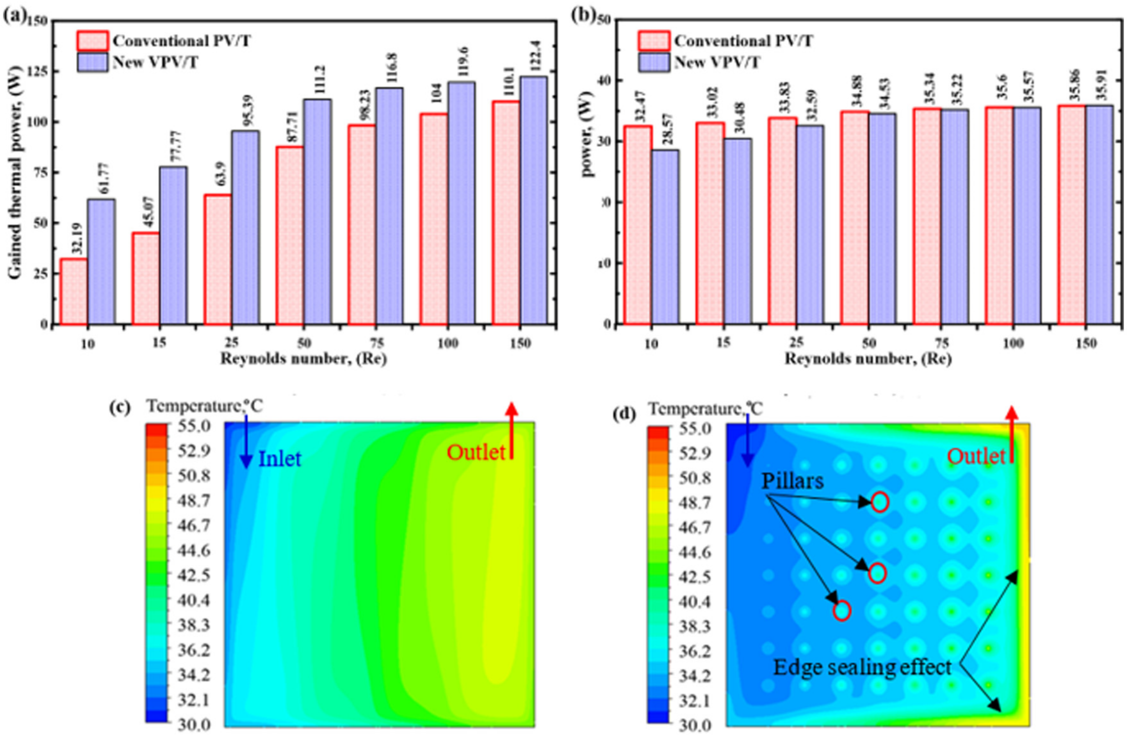

Fig. 4. Variation of (a) gained thermal power; (b) photovoltaic net gained electric power with the Re and temperature contours at Re of 50 for (c) PV/T and (d) VPV/T collectors respectively.

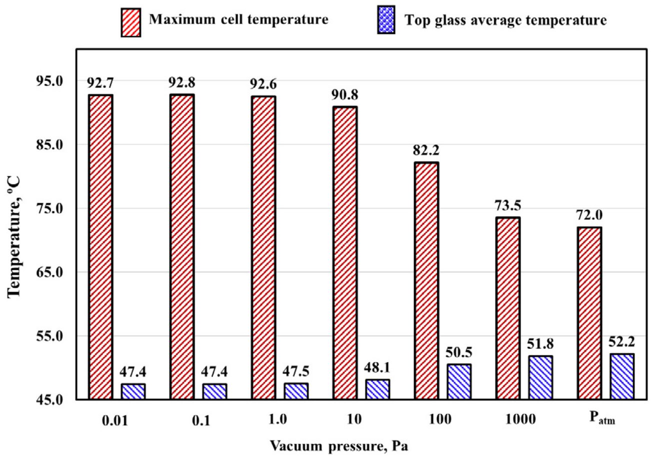

Fig. 5. Effect of vacuum pressure on the maximum cell temperature and the top glass temperature of the new designed VPV/T system.

4. Conclusions

In this study, the customary design of the PV/T collector is modified by including a vacuum layer above the silicon wafer. This new design proved to accomplish high thermal and electrical power compared to the conventional design of the PV/T collector. The thermal energy loss from the top surface of the collector is minimized. And this collector proved to attain a high performance even with a vacuum pressure up to 10 Pa. Optimal design, exergy analysis, and long-term simulation along with lower thermal conductive sealing material with practical implementation is of great importance for future work.

CRediT authorship contribution statement

Ali Radwan: Writing - original draft, Simulation, Validation. **Takao Katsura:** Funding acquisition, Conceptualization, Experimental facility, Software, Writing - reviewing. **Saim Memon:** Writing - review & editing, Analysing, Collaboration. **Essam M. Abo-Zahhad:** Formal analysis, Data curation, Writing - original draft, Editing. **Ahmed A. Serageldin:** Formal analysis, Data curation, Writing - original draft, Editing. **Katsunori Nagano:** Supervision, Editing, Conceptualization, Collaboration, Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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