Article

Experimental and theoretical evaluation of bifacial photovoltaic thermal collectors

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Abstract
This paper represents the theoretical and experimental performances of solar collector using an array of a single pass – air photovoltaic (PV) cells; replacing a diffuse reflector under a bifacial PV module (with an acceptable distance) instead of conventional absorber plate of photovoltaic-thermal (PVT) collectors. Energy and exergy analysis of the solar collector is done by mathematical modeling in one-dimensional steady state condition (1D-SS). A collector rack was designed and fabricated to examine and verify the theoretical model. The steady state exergy efficiency of 4.2 – 10% and energy efficiency 17 - 62% detected for both 0.04 - 0.13 kg/s and 0.22, 0.33, 0.50 and 0.67 of airflow rate and packing factor respectively. The prevailing output of the collector is thermal energy while electricity is the dominant output of exergy. In the range of 0.04 – 0.13 kg/s, airflow rate has no influence on the overall exergy of the collectors due to the strong dependency of the total exergy on electrical output rather than thermal one. Finally, as the result of increasing airflow rate, the overall output energy of the collector increases due to the increase of the thermal energy harvest.

Keywords photovoltaic thermal; air-based; bifacial solar cell; exergy; reflector.

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1 Introduction

The only difference between the photovoltaic (PV) and flat plate thermal collector is that the former has panels attached on the top of the metallic flat plate absorber. The PV cells are made of semi-conductor materials converting the high-energy photons of solar irradiation into the electricity.

Some researches done in 1980s resulted in some innovation in solar cells making them able to absorb the solar radiation from the back surface (Luque et al., 1980). The type of solar cells that absorbs incident radiation from both front and back surface of their collectors are called (Fig. 1), which have favorable advantages over the conventional (mono-facial) PV cells (Ooshaksaraei et al., 2011) in that they can produce up to 90% extra electricity in contract with the mono-surface cells (Joge et al., 2002). This electrical energy is heavily bank on the ability of reflector to provide proper radiation for the back aperture (Moehlecke et al., 2001; Duran et al., 2011).

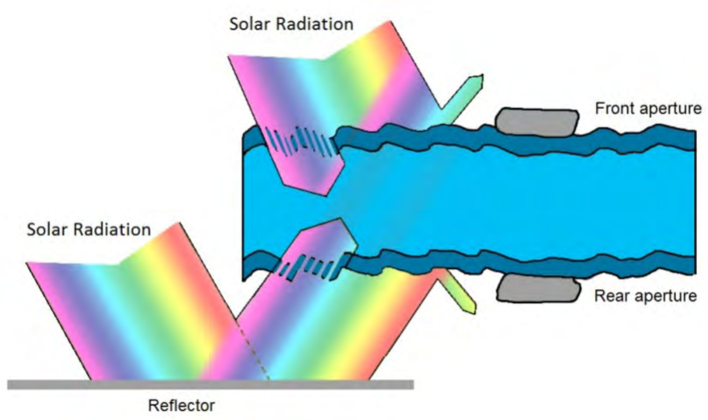

Fig. 1 Cross section view of bifacial photovoltaic solar cell (Sopian et al., 2017).

Reflection property of the reflector has a significant effect on the electrical energy output of the bifacial PV cell. In that way, white and yellow color collector surface has the largest reflection efficiency of 75% and 61% respectively (Moehlecke et al., 2001).

In general, a heat removal system, PV cells and an absorber plate are the three main parts of the PVT collector. However, the absorber plate which is installed behind the a PV cell (Sopian et al., 2002; Chow, 2009; Hasan and Sumathy, 2010; Kumar and Rosen, 2011; Zhang et al., 2012), can blind the back surface of the collector making them inappropriate for the bifacial cells (Ooshaksaraei et al., 2014). To solve this problem for PV cells, a reflector can be installed instead of an absorber plate and this makes the monofacial PV cell into bifacial one. On the other hand, the fewer number of solar cell will lead to the lower cost of a module (Uematsu et al., 2001). A challengeable goal can be designing a collector in that both front and rear surfaces receive a proper amount of solar radiation (Ooshaksaraei et al., 2013).

A semi-transparent solar PV cell with almost a comparable transparency with bifacial solar cells, whereas the rear aperture cannot produce electrical energy. In this way, only a portion of irradiation is absorbed by the cells and the absorber plate beneath the cells will absorb the rest of the penetrating radiation (Kamthania et al., 2011). The distance between the modules of the semi-transparent PV cells and the absorber plate can lead to a lower operation temperature compared to the attached absorber plate of monofacial PV cells (Park et al., 2010).

In order to evaluate the performance of a PVT solar collector, the two foremost significant factors including the total energy and exergy output of the PVT collector can be evaluated, although there are many parameters such as airflow rate, packing factor, and the number of glazing that have influence on the collector’s performance. However, the energy and exergy methods are based on the first and second law of thermodynamics respectively. Comparing with the thermal output energy of the PVT solar collector, the electrical output energy has higher efficiency by efficient conversion to work regarding the second law of thermodynamic (Chow et al., 2009). The operating setting and single design criteria are not the necessary conditions in which the optimal value (maximum value) of the exergy and energy outputs takes place. To find the maximum values of them, Sarhaddi et al. (2010) observed the maximum exergy output at 35°C, and the maximum energy output at 31°C by studying the inlet-air temperature effect on the performance of the PVT collector. A review on some of the energy and exergy efficiency of the previous studies is presented in Table 1.

Table 1 A short review on the result of energy and exergy efficiency of PVT solar collectors.

Collector Type	Energy efficiency	Exergy efficiency
PVT-air(Bosanac et al., 2003)	55%	13.5%
PVT-air(Joshi and Tiwari, 2007)	55% - 66%	12% - 15%
PVT-air(Joshi et al., 2009)	33% - 45%	11.3% - 16%
PVT-air(Sarhaddi et al., 2010)	45%	10.75%

At steady state condition and regarding the first and the second laws of thermodynamics, the current study evaluates the theoretical and experimental performance of an air-based, bifacial PVT solar collector with single path.

2 Mathematical Model

The main application of the single-path air-based PVT solar collectors is in hybrid. Whereas, the most of the available collector designs are inappropriate for bifacial PV modules. Fig. 2 displays a newly designed bifacial PVT collector. A reflector with 5 cm separation is installed beneath the PV panel instead of the traditional absorber plate; in which it has 75% reflection and 25% absorption.

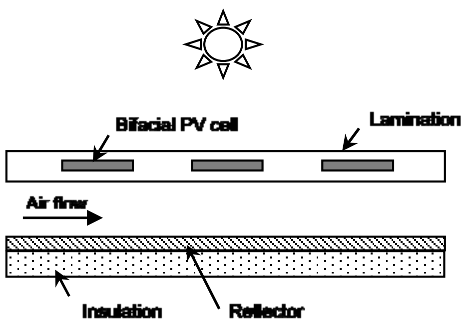

Fig. 2 Cross section schematic of the single path bifacial PVT collector (Ooshaksaraei et al., 2017).

Energy and exergy balance equations are proposed to show an analytical model for the all thermal, electrical as well as hybrid performance of the PVT panel.

2.1 Energy balance method

Regarding the first law of thermodynamics, energy balance method and equations are applied to calculate the performance of the bifacial photovoltaic thermal collector (Fig. 3).

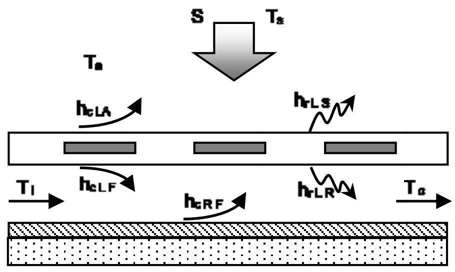

Fig. 3 Heat transfer coefficient of different parts of the of Single path bifacial PVT collector (Ooshaksaraei et al., 2017).

In Fig. 3, the, h_{cLF}, h_{cRF}, and h_{cLA} are convection heat transfer coefficients between PV laminate, reflector, working fluid, and ambient respectively; and h_{rLR} and h_{rLS} are radiation heat transfer confidents between PV laminate, reflector, and sky. Fig. 3 shows that the air flows into the distance between the lamination and the reflector plate at the T_i and flows out at T_o, with forced convection heat transfer mode. On the top surface of the PV laminate, there would be a heat loss that can be caused by the natural convection with ambient air. However, a study on different configurations of photovoltaic thermal collectors having a typical rear insulation (0.025 m thick polystyrene sheet; k = 0.04 W. m^{-1} K^{-1}) displayed that the overall back loss coefficient doesn't have an appreciable effect on expected temperatures in a PVT collector (Ong, 1995). In this research, it is assumed that the collector is well isolated at both top and rear sides. The energy balances (per unit area) for PV laminate, reflectors and fluid are demonstrated in equations 1 through 3 respectively.

$$S\alpha_{PV} P(1-\eta_{PV_{front}}) + S(1-P)P\alpha_{PV}(1-\eta_{PV_{rear}})\eta_R \tau_L = \\ h_{cLa}(T_L - T_a) + h_{cLF}(T_L - T_F) + h_{rLS}(T_L - T_S) + h_{rLR}(T_L - T_R) \tag{1}$$

conversion rate of solar energy into heat on top side of PV cell
+
The rate of solar energy transmitted through the vacant space between PV cells, reflected back by reflector and transformed to heat by back side of PV cells

=

The rate of free convection heat transfer from front side of PV laminate to the ambient
+
The rate of forced convection heat transferfrom back side of PV to flowing air
+
The rate of radiative heat transfer from PV laminate to the Sky
+
The conversion rate of radiative heat tarnsfer from PV laminate to reflector

$$h_{rLR}(T_L - T_R) + S(1-P)(1-\eta_R)\tau_L = h_{cRF}(T_R - T_F) + U_R(T_R - T_a) \tag{2}$$

conversion rate of radiative heat tarnsfer from PV laminate to reflector
+
The rate of solar energy transmitted through the vacant space between PV cells,and transformed to heat by reflector

=

The rate of forced convection heat transfer from reflector to flowing air
+
An overall heat loss from back side

$$h_{cLF}(T_L - T_F) + h_{cRF}(T_R - T_F) = \frac{\dot{m}C_F}{B}\frac{dT_{F_i}}{dTx_i} \tag{3}$$

The rate of forced convection heat transfer from back side of PV laminate to flowing air)
+
The rate of forced convection heat transfer from reflector to flowing air)

=

The heat carried away with the flowing air

The electrical efficiency of bifacial PV panel is given as

$$\eta_{Electrical} = \eta_{Electrical\ front} + \eta_{Electrical\ rear} \tag{4}$$

where, it depends on photovoltaic cell operation temperature (Sarhaddi et al., 2010)

$$\eta_{Electrical_{front}} = \eta_{Electrical_{rear}} = \eta_{ref}\left[1 - \beta_{ref}\left(T_{Cell} - T_{ref}\right)\right] \tag{5}$$

It is proposed that the thermal efficiency of the collector is comparable to the ratio of harvested thermal energy over the total solar radiation reaching the collector surface

$$\eta_{Thermal} = {\dot{m}C_p(T_o - T_i)}/{S \times A} \tag{6}$$

In addition, the electrical energy should be included into the total efficiency equation since it has a higher value than thermal energy (Shahsavar and Ameri, 2010)

$$\eta_{Total} = \eta_{thermal} + {\eta_{Electrical}}/{\eta_{PowerPlant}} \tag{7}$$

where $\eta_{PowerPlant}$ is the efficiency of conventional power plants (Ji et al., 2007). Hence, to evaluate the performance of the collector in the form of thermal energy, the electrical energy should be transformed into thermal energy based on what efficiency is required for the power plants.

2.2 Exergy method

Considering the second law of thermodynamics, the operation temperature of solar panel has great impact on the output value of thermal energy. In general, the output exergy of a PVT collector is the summation of electrical exergy and thermal exergy(Fujisawa and Tani, 1997)

$$Ex_{Out} = Ex_{El} + Ex_{Th} \tag{8}$$

where Ex_{El} is the electrical exergy that should be comparable to electrical energy (En_{El}) for that the electrical energy should be converted into work efficiently (Chow et al., 2009)

$$Ex_{El} = En_{El} \tag{9}$$

Instantaneous electrical energy/exergy generated is

$$Ex_{El} = En_{El} = AS\,\alpha_{PV}\,P\,\eta_{PV_{front}} + AS\,(1-P)\tau_L\eta_R P\,\alpha_{PV}\eta_{PV_{rear}} \tag{10}$$

Instantaneous electrical energy

=

The rate of solar energy (transformed to electricity by front side of PV cells)
+
The rate of solar energy transmitted through the vacant space between PV cells, reflected back by reflector and transformed to electricity by back side of PV cells

where "P" proposed that solar cells covers only a portion of the PV panel but not the entire surface of it. The overall electrical efficiency of the PV panel depends on the packing factor (P) in which when it increases the temperature of the PV panel will reduce (Chow, 2003; Zondag et al., 2003; Agrawal and Tiwari, 2011). In addition, the thermal exergy of a solar collector can be calculated though equation 11 (Borel and Favrat, 2010)

$$Ex_{Th} = \dot{m}C_p\left[T_2 - T_1 - T_a\left(\ln\frac{T_2}{T_1} + {\gamma-1}\big/{\gamma}\,\ln\frac{P_1}{P_2}\right)\right] \tag{11}$$

where T_a is the ambient temperature and can be used as a reference point to find the exergy. Also, T_a can be applied as an input to estimate the maximum theoretical work based on the thermal energy output of a solar collector (Bejan et al., 1996). In that the solar radiation exergy (Petela, 2003) and the exergy efficiency are defined in equation 12 and 13 respectively (Hepbasli, 2008; Nayak and Tiwari, 2008; Borel and Favrat, 2010; Sarhaddi et al., 2010)

$$Ex_{Sun} = S\left[1 - \frac{4}{3}\left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4\right] \tag{12}$$

$$\eta_{Ex} = \frac{Ex_{out}}{Ex_{Sun}} \tag{13}$$

3 Experimental Setup

A bifacial PVT collector rack was designed, fabricated, and tested under halogen lamp solar simulator. The objective of the experiment is to study the performance of newly designed bifacial PVT collector in a controlled environment with its specifications; and prove the validity of the mathematical model. The experimental setup and the related components are shown in Fig. 4. The main components which are shown in Fig. 4 include: thermal collector, titling mechanism, support structure, air flow sensor, sensor for temperature and radiation measurement, data acquisition device, DC current voltage and IV curve plotter.

The "air-based bifacial photovoltaic thermal solar collector" is made of stainless steel sheet with elastomeric nitrile rubber stuck to both body of collector and inlet/outlet air channels. The conventional flat aluminum sheet is placed with specific separation beneath bifacial PV panel while the top surface of the PV panel is covered with glass (Table 2).

Table 2 dimensions of different parts of the setup.

Specification	Dimension
stainless steel sheet	0.001m thickness
elastomeric nitrile rubber	3/8 in
aluminum sheet	0.002 m thickness
Separation of PV panel	0.050m
tempered glass	0.008m

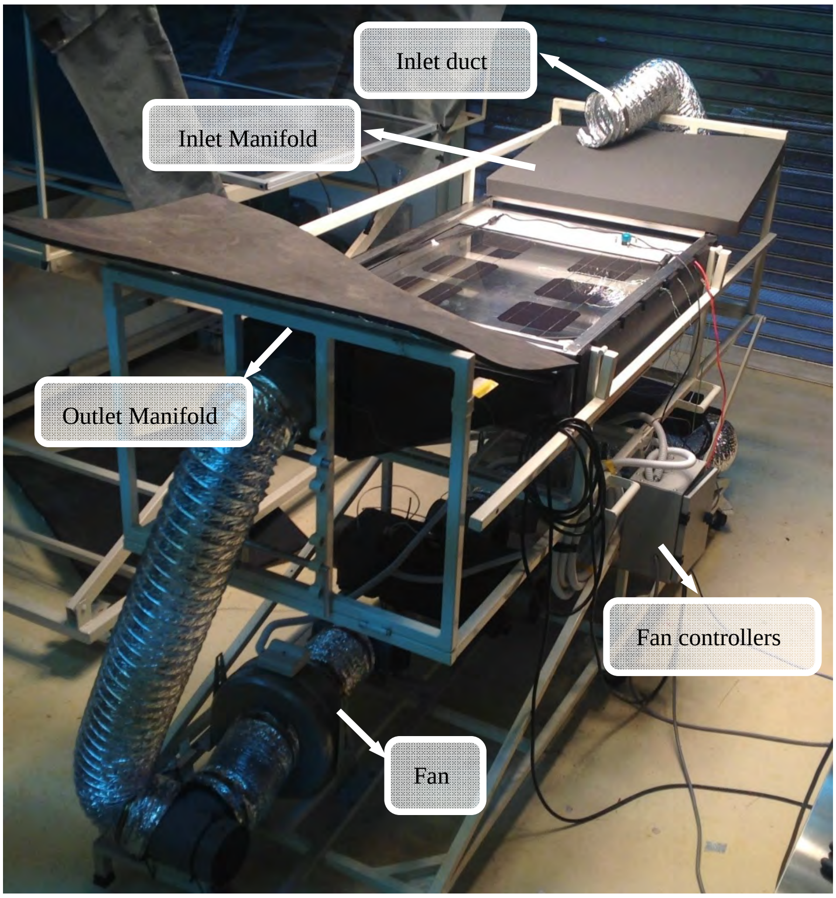

Fig. 4 The bifacial PVT collector give (Ooshaksaraei et al., 2017).

The interface of data acquisition system was developed in the well-known "Labview" program. Photovoltaic panels as the main part of the system can absorb solar radiation and play the role of a simple solar collector in this setup. Four different configurations are designed to evaluate the effect of packing factor (P) on performance of the photovoltaic collectors (Table 3) under the STC conditions of 1000 W/m^2 and 25ºC cell temperature.

Table 3 PVT collector design parameters and characteristics.

Parameters	Value			
The number of cells in the panel	4	6	9	12
The electrical efficiency at the reference conditions	0.16			
Material	Mono-crystalline silicon			
The thickness of the PV panel glass cover	0.003m tempered			
The packing factor	0.22	0.33	0.50	0.67

4 Results and Discussion

4.1 Verification and mathematical model

Under steady state condition the mathematical model simulated the air based PVT system in order to compare the experimental and theoretical results using energy analysis method. All values of absorptivity, emissivity, and transmissivity for various surfaces are applied using the measurements in previous studies. However, by modifying those values, the trivial temperature difference of 1°C or less for the thermal collector could be obtained (Sopian, 1997). This means that this model does not have a tight dependency on these values. On the experimental side, the values of T_{in} , T_{out} ,T_r ,T_{PV} ,V_{air} , $P_{max,PV}$ and I_r are measured. Fig. 5 shows the behavior of the fluid temperature along the length of the panel which is one meter and is divided in to 100 points. The air temperature increased 1.7°C under 800 watts solar radiation, while the air flow rate is 0.083 kg/sec and the packing factor is 0.5. The total efficiency was 39%.

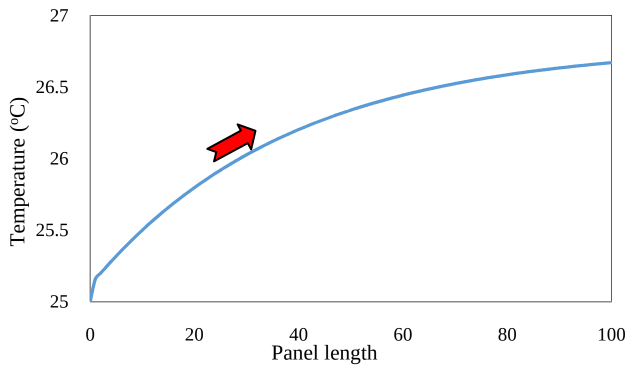

Fig. 5 Experimental result of the airflow temperature gradient along the length of the thermal collector.

The electrical and thermal efficiencies of the thermal collector are calculated using the static simulation and compared with the experimental results with respect to airflow rate and packing factor. The efficiencies of the PVT collector for two packing factors 0.22 and 0.67 are shown in Fig. 6 in that the efficiency would increase with increase of air mass flow rate as reported by other researchers (Sopian et al., 2000; Tiwari and Sodha, 2007).

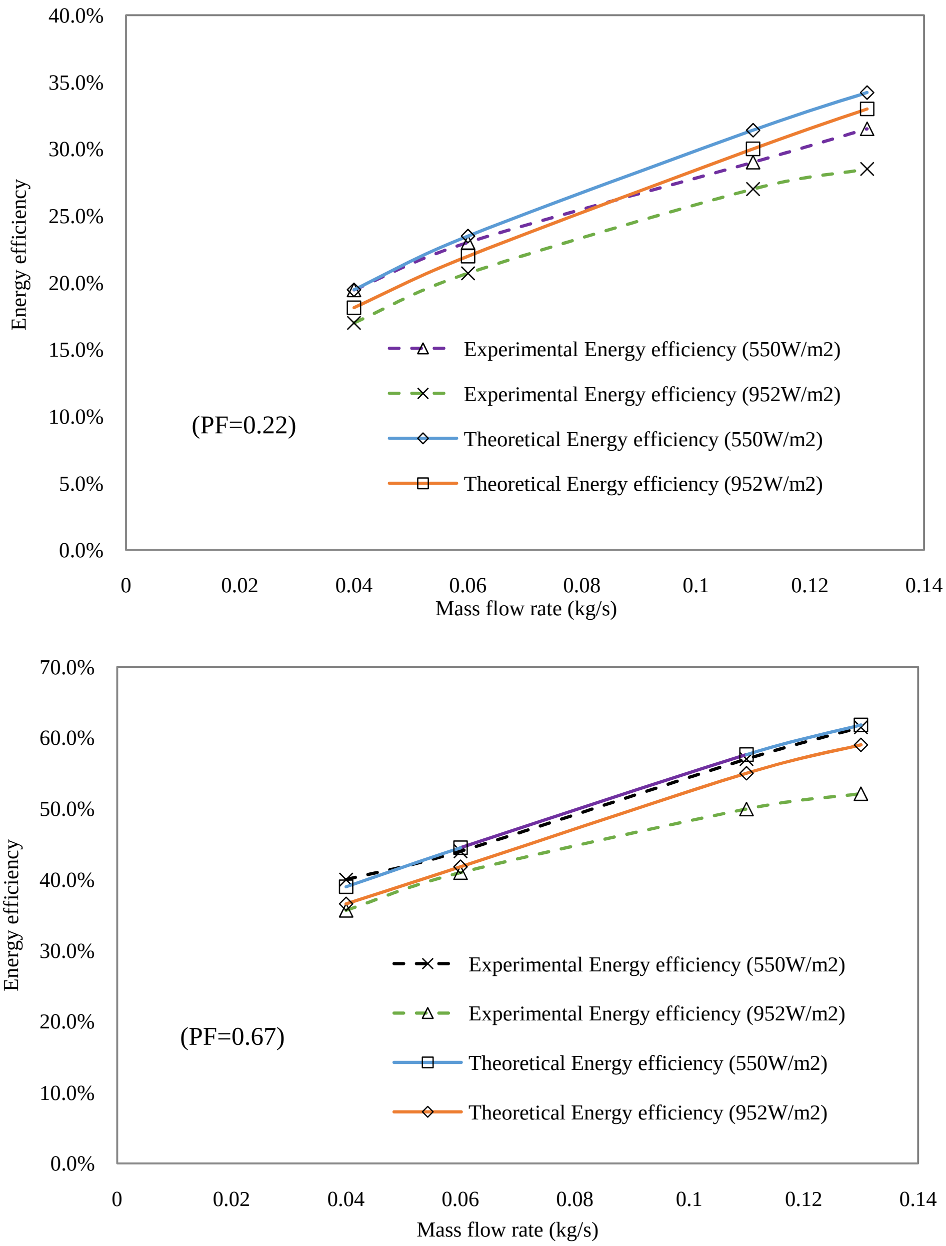

Fig. 6 Theoretical and experimental photovoltaic thermal efficiency comparison for packing factors 0.22 and 0.67.

The simulation and experimental results have similar trend, as shown in Fig. 6. However, the experimental results are slightly lower than that of the simulation one. It is attributed to possible air leakage into the airflow system and collector from clearance in between components. This air intake can turn the output air temperature cold and have impact on data reading. A high rate of airflow confirms that the thermal collector can operate at lower temperatures that will lead to less thermal dissipation into air making high rate preferable over the low rate airflow. The similar results have been proved for a mono-facial single-pass PVT air heater (Sarhaddi et al., 2010).

4.2 Exergy method

There are six equations, 8 through 13, and six unknowns that can be solved by exergy simulation method. The total exergy output for different packing factor of the photovoltaic thermal collector in this study is shown in Fig. 7.

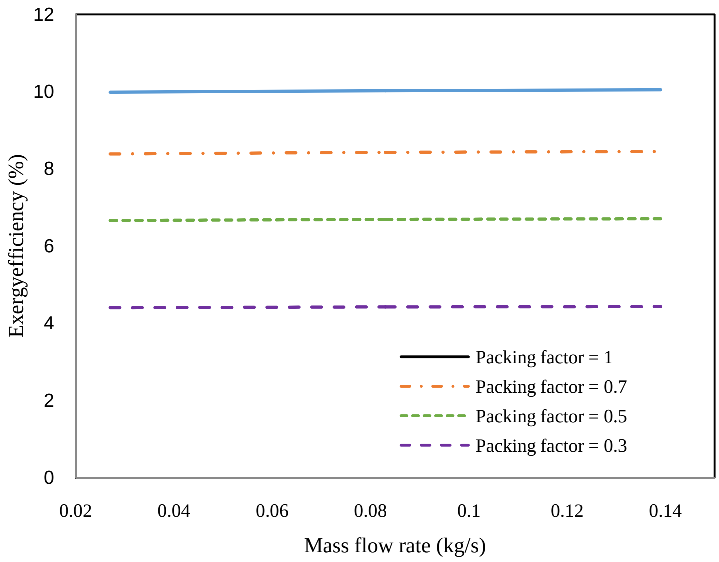

Fig. 7 The total exergy efficiency of bifacial PVT collector.

Fig. 7 shows that increase in mass flow rate has no considerable effect on increase of exergy efficiency of the thermal collector and the higher packing factors have higher exergy efficiency. For example, the maximum and minimum exergy efficiency of 10% and 4.2% are achieved for the packing factor of 1 and 0.3 respectively. Comparing Figs 6 and 7, it can be seen that by increasing the mass flowrate the energy efficiency improves the energy efficiency and achieved the maximum value of almost 60% for packing factor of 0.67. The main reason is that the thermal energy is the dominant form of energy output of the thermal collector while electrical output is the dominant exergy output of a PVT panel. In other words, when packing factor decreases from 0.67 to 0.3, practically the number of silicon wafers increase up to 133%, while it generates the same amount of additional exergy (100%). In this research, the reflector is located beneath the bifacial PV panel, which indicates that the rear aperture of the bifacial PV panel with packing factor 1 has no impact on the electrical energy of the whole system.

5 Conclusion

A flat plate bifacial photovoltaic thermal collector was designed by installing a diffuse reflector beneath the PV lamination. The mathematical model was developed based on the first law and second laws of thermodynamic at one-dimensional under steady state conditions. An experimental rack has been developed to verify the mathematical model at indoor test condition under halogen lamp solar simulator. The simulation result is in accordance to the experimental ones. The total efficiency 17% - 62% observed for the airflow rate 0.04kg/s - 0.13 kg/s, and packing factor 0.22 - 0.67. While the exergy efficiency is 4.2 – 10%. The energy efficiencies increase by increasing the packing factor. High packing factor results into a higher solar energy absorption and a higher PV cell temperature consequently, which has impact on both, energy and exergy outputs. In addition, high packing factors causes less vacant space between the PV cells, which culminates into less solar radiation absorbed by the rear surface of the cells, and less energy and exergy production resulted from the rear PV cell surface consequently.

6 Nomenclatures, Abbreviation and Acronyms

A	collector area (m^2)
C_p	specific heat capacity of Air (kj/kg.K)
En	energy rate (W)
Ex	exergy rate (W)
h	heat transfer coefficient W/m^2K
$\dot{m}$	Flow rate (kg/s)
PF	packing factor
S	solar radiation intensity (W/m^2)
T	temperature (°C)
T_{in}	Inlet air temperature (°C)
T_{out}	Outlet air temperature(s) (°C)
T_r	Room temperature (°C)
T_{PV}	PV panel temperature (°C)
V_{air}	Air velocity (m/s)
$P_{max,PV}$	Maximum power production by PV panel (W)
I_r	Radiation intensity (W/m^2)

Greek Symbols

η	efficiency (%)

Superscript

a	ambient
c	convection
front	front aperture of the PV cell
i	Inlet
l	laminate
El	electrical
F	air stream
o	outlet
PV	photovoltaic
ref	reference condition (25°C)
r	radiation
rear	rear aperture of the PV cell
R	reflector
s	Sky
Th	thermal
PVT	Photovoltaic thermal

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