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Effect of Using Packing Material on the Performances of the Double Pass Photovoltaic-Thermal (PVT) Air Heater

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Abstract

The current work aims to demonstrate the effect of the packing material on the performance of the double pass (PVT) solar air heater in terms of energy and exergy. In addition, the influence of porosity and air mass flow rate is also evaluated. A theoretical analysis for the system with and without packed bed has been presented. A numerical simulation program developed in Matlab 2012 has been performed for the solution of the thermal model. The latter is applied for a sunny day (15 June) on the basis of the climatic conditions of Jijel (east of Algeria, Latitude 36.52 ° N, Longitude 6.57 ° E). The results show that the presence of packing material in the lower channel of double pass photovoltaic-thermal (PVT) air collector increases the convective heat transfer. This improves the energy and exergy performance. Under the same conditions, the PVT system with packed bed provides higher overall thermal efficiency, which is better of about 11-13% compared to the system without packed bed.

Keywords: *Packing material, Performance, Double pass, Hybrid solar collector.*

1. Introduction

After the OPEC oil embargo in 1973/1974, many governments have found a strong motivation to move towards renewable energies such as photovoltaic thermal production by the PVT solar collector. As indicated by Hendrie, The first study on a PVT system was presented by Martin Wolf in 1976 [2]. The development of this system has experienced a decline period due to the collapse of oil price in 1982, before finding a second wind in 1997 after the signing of the Kyoto Protocol. The latter contributed significantly to revive many projects and commitments in several countries in the field of PVT.

In the literature several studies have been performed on the PVT solar air heater, some of these studies focus on the evaluation of thermal and electrical performance and others on the development of analytical thermal models. Kern and Russel, gives the basic principles of hybrid solar collectors using water or air as the working fluid. Garg and Adhikari [3] have proposed a modeling program in order to predicate the transient performance of PVT air heating collector with single and double glass configurations. Then, Mei et al [4] presented the dynamic model based on TRNSYS for a building with an integrated ventilated PV facade/solar air collector system. Later, a theoretical and experimental study of a hybrid photovoltaic/thermal (PVT) system has been presented by Tiwari et al [5]. The analysis results showed that using of additional thermal energy produced in PV, improves the overall performance of PVT air from about 18%. Vokas et al [8] conducted a theoretical study of a solar PVT hybrid air by focusing on its thermal performance. In order to increase the thermal and electrical performance of hybrid PV/thermal air collector, many configurations have been proposed in the works of Hegazy [11] Tiwari, Sodha [6], Trip Anagnostopoulos [10], Othman et al [9] and R Kumar et al[12].

Performance evaluation of a solar hybrid air collector can be also performed by an exergy analysis. Joshi et al [7] presented the study of energy and exergy efficiencies of unglazed PV/thermal air with Tedlar. They concluded that there is an increase of about 2–3% exergy due to thermal energy in addition to its 12% electrical output from PVT system, which makes an overall electrical efficiency of about 14-15% of PVT system. Sanjay Agrawal et al [13], then presented an evaluation of energy and exergy performances of hybrid photovoltaic thermal micro-channels (MCPVT) under different

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climatic conditions of India. It was observed that an overall annual thermal and exergy gains have been increased by 70.62% and 60.19% respectively for the module MCPVT under the climatic conditions of Srinagar. Similar observations have been taken to Bangalore, New Delhi and Jodhpur.

In this work an energy and exergy analysis has been carried out to calculate the performance of a double pass PVT solar air heater with and without packed bed. The results of numerical simulation are used like a tool to predict the effect of the packing material on one hand, and to show the influence of the porosity and mass air flow rate on the performance of the double pass (PVT) solar air heater in terms of energy and exergy, on the other hand.

2. Description of System

The structures of the double pass HPVT air collector with and without packed bed are presented in Fig. 1. These systems have the same basic configuration. The only difference in the tow designs is the lower channel (with and without packing material). The based system consists of:

- A transparent cover allowing sunlight to pass towards the absorber and forming the upper channel.
- A photovoltaic cell for the production of electricity. It is integrated above the absorber forming an absorbent surface (absorber / cell surfaces).
- A heat insulator allowing limiting the losses by conduction through the walls back and side.

The air enters through the channel formed by the glass cover and the PV plate and then through the lower channel.

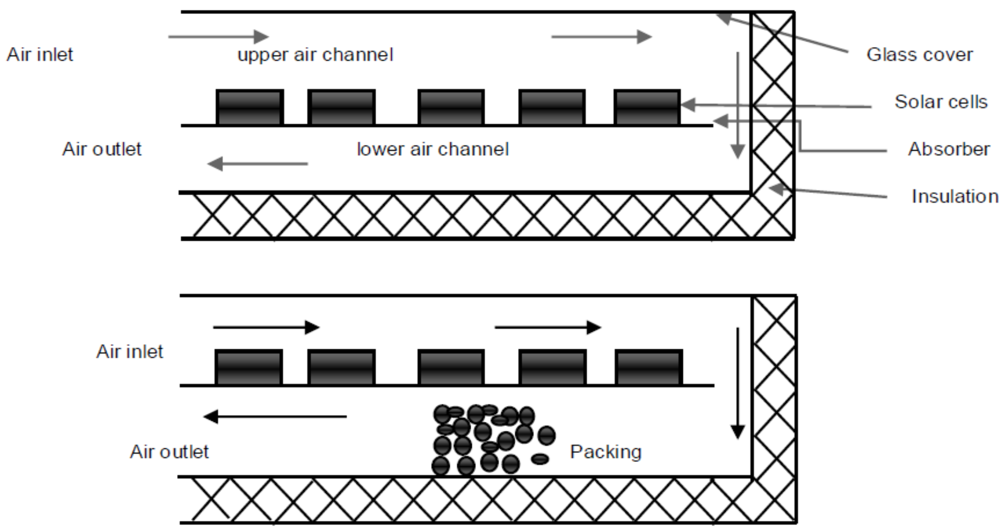

Fig. 1. Cross-sectional view of double-pass PVT solar air heater with without packed bed

3. Energy analysis

The energy analysis allows to determinate the thermal and electrical performances of the proposed systems. To simplify this analysis the energy balance has been made by basing itself on the following hypotheses:

- The systems operate under steady state conditions.
- The heat capacities of the glass cover, absorber plate, back plate and insulation are negligible.
- The air temperature varies only in the direction of flow (x-direction).
- No temperature gradient across the thickness of the glass covers, absorber and back plates.
- The absorber and cells are in equilibrium thermal.
- Sky temperature is assumed to be equal to ambient air temperature.

The energy balance equations for each component of (PVT) solar air heater are given as follows:

Glass cover:

$$\alpha_g I + h_{rabg}(T_{ab} - T_g) = h_{rgs}(T_g - T_s) + h_{cgw}(T_g - T_a) + h_{cgf1}(T_g - T_{f1}) \quad (1)$$

The air of the first channel:

$$\frac{\dot{m}C_p}{w_1}\frac{dT_{f1}}{dx} = h_{cabf1}(T_{ab} - T_{f1}) + h_{cgf1}(T_g - T_{f1}) \quad (2)$$

w_1 : The width of the upper channel [m].

T_{ab} : The temperature of the absorber surface [°C].

Absorber / cell surfaces (case of system with packed bed):

$$(1-PF)I_p + (1-\eta_{el})PFI_{pv} = h_{rabg}(T_{ab} - T_g) + h_{cabf2}(T_{ab} - T_{f2}) + h_{rabi}(T_{ab} - T_i) + h_{cabf1}(T_{ab} - T_{f1}) + h_{rabp}(T_{Tab} - T_p) \quad (3)$$

PF : The packing factor.

Absorber / cell surfaces (case of system without packed bed):

$$(1-PF)I_p + (1-\eta_{el})PFI_{pv} = h_{cabf2}(T_{ab} - T_{f2}) + h_{rabg}(T_{ab} - T_g) + h_{rabi}(T_{ab} - T_i) + h_{cabf1}(T_{ab} - T_{f1}) \quad (4)$$

Where I_p , I_{pv} are the amounts of solar irradiance absorbed by the absorber and photovoltaic cells respectively. These relations can be written as follows:

$$I_{pv} = \alpha_{pv}\tau_g I \quad (5)$$

$$I_p = \alpha_p \tau_g I \quad (6)$$

The air of the lower channel (case of system with packed bed)

$$\frac{\dot{m}C_p}{w_2}\frac{dT_{f2}}{dx} = h_{cabf2}(T_{ab} - T_{f2}) + h_{cif2}(T_i - T_{f2}) + h_{cpf2}(T_p - T_{f2}) \quad (7)$$

Here w_2 is the width of the lower channel.

The air of the lower channel (case of system without packed bed)

$$\frac{\dot{m}C_p}{w_2}\frac{dT_{f2}}{dx} = h_{cabf2}(T_{ab} - T_{f2}) + h_{cif2}(T_i - T_{f2}) \quad (8)$$

The insulating material (case of system with packed bed)

$$h_{rabi}(T_{ab} - T_i) + h_{rpi}(T_p - T_i) = h_{cif2}(T_i - T_{f2}) + U_i(T_i - T_a) \quad (9)$$

The insulating material (case of system without packed bed)

$$h_{rabi}(T_{ab} - T_i) = h_{cif2}(T_i - T_{f2}) + U_i(T_i - T_a) \quad (10)$$

The packing material

$$h_{rabp}(T_{ab} - T_p) + h_{rpi}(T_i - T_p) = h_{cpf2}(T_p - T_{f2}) \quad (11)$$

T_a : The ambient air temperature.

Its corresponding boundary conditions are:

$$T_{f1} = T_{in} \qquad \text{at} \quad x=0 \quad (12)$$

$$T_{f2} = T_{f1} \qquad \text{at} \quad x=L \quad (13)$$

The knowledge of the heat transfer coefficients turns out to be necessary for the resolution of the model.

The various convective and radiative heat transfer coefficients used in Esq. (1), (3), (4), (9), (10), (11) and noted (h_{rabg} , h_{rgs} , h_{cgw} , h_{rabi} , h_{rabp} , h_{rip}) can be calculated by using the correlations given in the literature[1].

The forced convective heat transfer coefficients for the air flow in the upper channel are given according to Nusselt, and the hydraulic diameter of the duct by the relation[16]:

$$h_{cgf1} = h_{cabf1} = \frac{Nu\,k_f}{D_h} \quad (14)$$

Where:

$$Nu = 0.0333\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \quad (15)$$

In case of system without packed bed, the forced convective heat transfer coefficients (h_{cif2} and h_{cabf2}) existing in the lower channel are also calculated by using Esq.14and 15.

In case of system with packed bed, the air/wall heat transfer coefficients existing in the lower channel are correlated as [15]:

$$h_{cif2} = h_{cabf2} = \frac{Nu_p\,k_f}{D_p} \quad (17)$$

Where:

$$Nu_p = 0.2\,\mathrm{Re}_p^{0.8}\,\mathrm{Pr}^{1/3} \quad (18)$$

The heat transfer coefficient between air and packing may be obtained from [15]:

$$Nu_p = \frac{h_{cpf2}\,k_f}{D_p} = \frac{0.225}{P}\mathrm{Re}_p^{0.8}\,\mathrm{Pr}^{1/3} \quad (19)$$

Where:

D_p : Packing diameter (m).

P : Porosity, which is the void volume to the total volume of channel.

The bottom heat transfer coefficient is given as:

$$U_i = \frac{k_i}{e_i} \quad (20)$$

k_i , e_i are the thermal conductivity and thickness of bottom insulation, respectively.

The thermal efficiency of combined photovoltaic thermal, which is by definition the produced energy quantity to the total power absorbed by the absorbent surface, can be obtained experimentally by the following formula:

$$\eta_{th} = \frac{\dot{m}C_p(T_{fo} - T_{in})}{A_c G} \quad (21)$$

Where T_{fo} , T_{in} are successively the outlet and inlet air temperature.

$\dot{m}$: The air flow rate (kg/s).

C_p : The specific heat of air (J/kg K).

A_c : The collector area (m^2).

The electrical efficiency, which is a linear function related to the cell temperature, can be evaluate as follow:

$$\eta_{el} = [1 - 0.0045(T_{ab} - T_{ref})]\eta_{ref} \quad (22)$$

Where T_{ref} is the reference temperature, η_{ref} is the reference efficiency of the PV module (taken equal to 0.16).
The overall thermal efficiency of PVT is defined by the following formula:

$$\eta_t = \eta_{th} + \frac{\eta_{el}}{0.4} \quad (23)$$

Here 0.4 is the conversion factor of the thermal power plant.

4. Exergy Analysis

The exergy of a thermodynamic system is a function that expresses the capacity of this system to produce work because of its disequilibrium with the environment in which it is located. In systems that operate irreversibly, exergy is always destroyed by creating a quantity called anergy. This quantity is significant when the destruction of exergy is important.

In our study we chose to evaluate the total exergetic efficiency, which is determinate as follows [14]:

$$\eta_{tex} = \eta_{th}\left(1 - \frac{T_a}{T_{fo}}\right) + \eta_{el} \quad (24)$$

5. Results and Discussion

In this study, a numerical simulation program developed in Matlab 2012 has been performed under Jijel (East of Algeria; Latitude 36.52 ° N, Longitude 6.57 ° E), where meteorological parameters have been selected for the day of June 15th.

The physical values used in this study are given as follow:

Table 1. Values of various parameters used in the performance evaluation.

Parameters	Values
Length of air heater	1.5 m
Width of air heater	0.75 m
Height of channels	0.09 m
Absorbtivity of glass	0.04
Emissivity of upper glass	0.85
Absorbtivity of absorber	0.96
Absorbtivity of photovoltaic cells	0.92
Nominal efficiency of PV cells	0.16
Thickness of bottom insulation	0.05m
Packing diameter	0.01m
Porosity	0.9

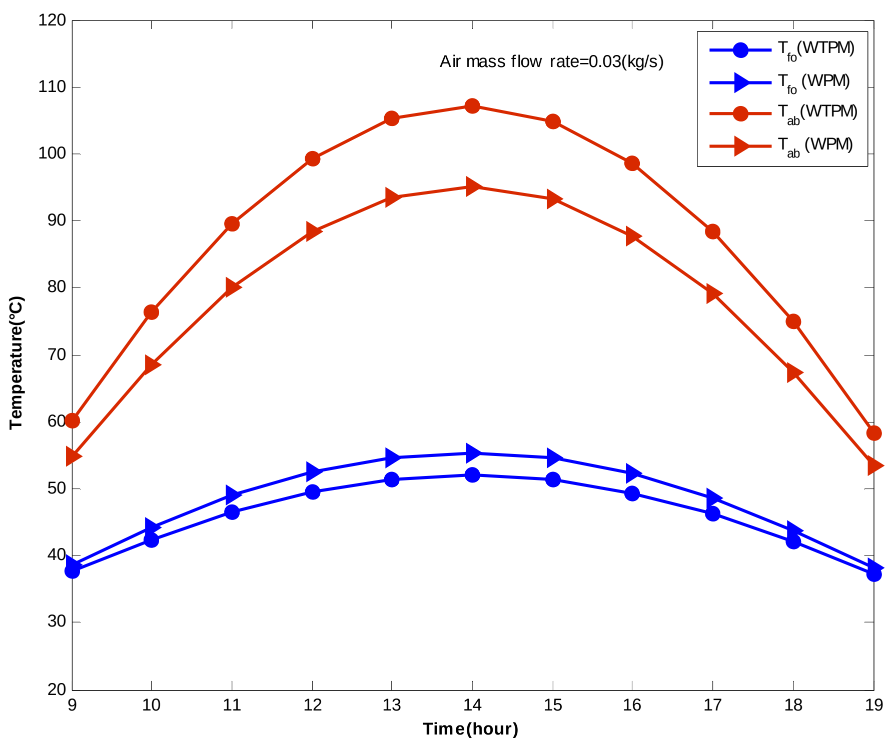

Fig.2. Temporal variations of the cell and outlet temperatures for a solar PVT system with and without packed bed.

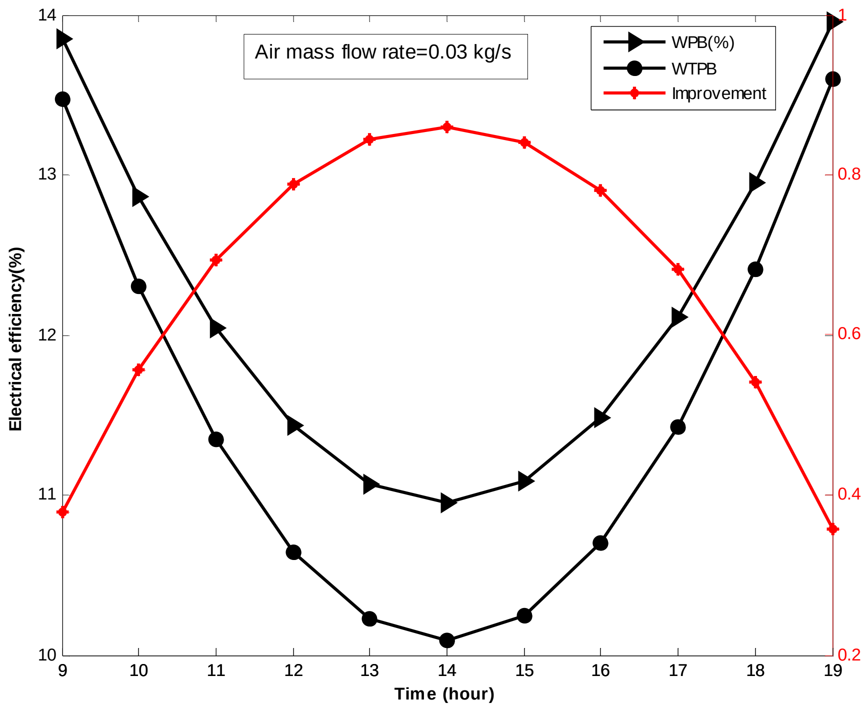

Fig. 3. Comparison between the electrical efficiency of double pass photovoltaic/thermal air heater with and without packed bed

Temporal variations of the cell and outlet air temperatures are illustrated in Fig. 2. for the solar PVT system with and without packed bed. From this figure, it's noted that the highest temperature is that of the absorbent surface, resulting of the significant power which it has absorbed. Its value is much lower in case of the system with packed bed. It's also noted that the PVT air collector with packed bed provides higher outlet air temperature compared to that without packed bed. Consequently, the use of packing material contributes to improve the convective heat transfer, which leads to reduce the temperature difference between the absorbent surface and outlet air.

Fig.3. shows the effect of packing on the electrical efficiency during the chosen day. It's observed that the electrical efficiencies of the system with and without packed bed decrease with time up to minimum values at 14h, and then increase in the rest of the day. By connection with fig.2, this result may be explained by the fact that, when absorbent surface temperature increases, the electrical efficiency decreases, and vice-versa. It's obvious that the electrical efficiency is higher in case of solar hybrid PVT collector with packed bed. The electrical efficiency improvement is defined by the following equation:

$$\eta_{elI} = \eta_{elSWB} - \eta_{elSWTB} \tag{25}$$

It's clear from the figure 3 that the electrical efficiency improvement increases with time as the solar radiation increases and takes its maximum at 14h.

In order to know the packing effect on the thermal performaces of double pass (PVT) air collector, one traces the instantaneous thermal and overall thermal efficiency for PVT air collector with and without packed bed. It's seen from the results of fig.4 that the thermal efficiency is in the range of 19-20% for the system without packed bed whereas it is of the order of 29-31% in the other case. Therefore, the use of the packing material increases the thermal efficiency from about 10%. For both systems, the overall thermal efficiency for PVT air collector is calculated from equation (20); its curve follows the same shape as the curve of electrical efficiency represented by figure 3. By connection with figure 3, it can be concluded that the electrical efficiency variation is more dominant over the thermal efficiency change throughout the day. In addition to these results, the overall thermal efficiency for system with packed bed is 11 to 13% higher than that without packed bed.

Fig. 4.shows the hourly variation of exergetic efficiency for system with and without packed bed. For both systems, we observe that the exergetic efficiency decreases with time in a parabolic manner and shows its minimum value at 14h, then rises again until the end of the day. Its temporal variation is similar to that of electrical efficiency (see Fig.3).The exergetic efficiency for system with packed bed lies between 13.7-15.2% and it lies between 11.7-14.3% for system without packed bed. It is easy to see that the use of the packing has a positive influence in improvement of the exergetic efficiency. This influence would be more significant for higher solar radiation. The effect of the packing material is much related to the porosity. The results presented in the rest of our study (see Figs. 5 to 8) shows the influence of the porosity and air mass flow on the energy and exergy performance.

Figs 5, 6 and 7 present the variation of thermal, electrical and overall thermal efficiencies with porosity and mass air flow. It appears that the increase of air mass flow rate results an increase of the thermal, and electrical efficiencies, for all studied porosities. Consequently, the overall thermal efficiency is also increased. It's also observed that the thermal and electrical efficiency of system increases with decreasing porosity. This may attributed to the increase of the convective heat transfer. Moreover, the highest overall thermal efficiency is obtained for the weakest porosity. The overall thermal efficiency increases up to about 76.6%, at a porosity of 0.3, when the mass flow rate increases from 0.02 to 0.1 kg/s. Furthermore, the influence of porosity is more notable at low flow rates compared to high flow rates.

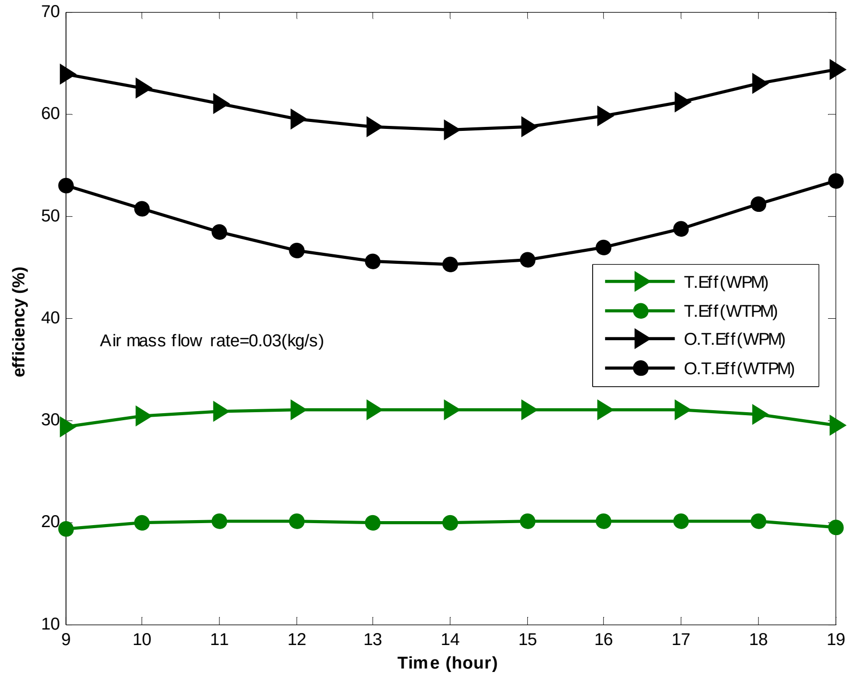

Fig. 4. Hourly variation of thermal efficiency for a solar PVT air collector with and without packed bed

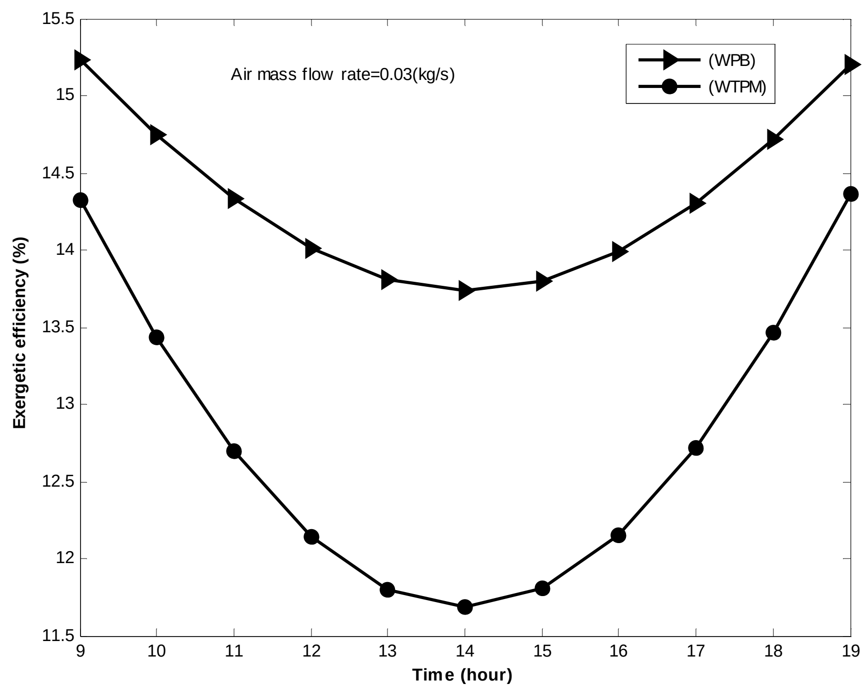

Fig. 5. Hourly variation of exergetic efficiency for PVT air collector with and without packed bed

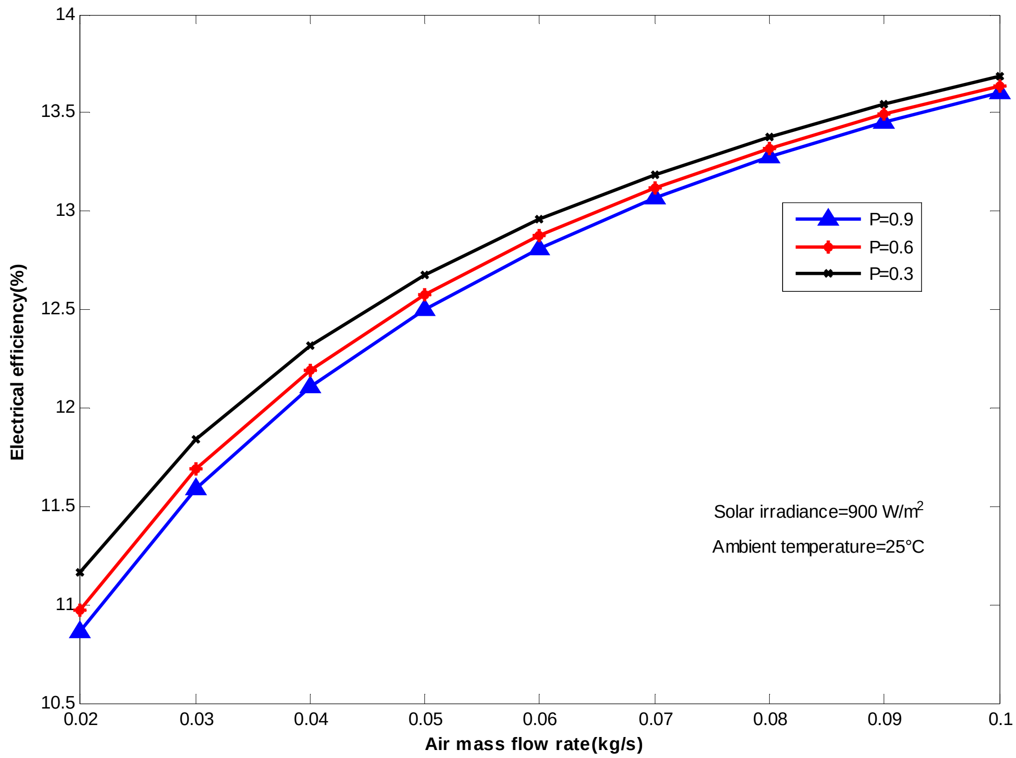

Fig. 6. Sensitivity of electrical efficiency with respect to changes of mass flow rate and for values of porosity

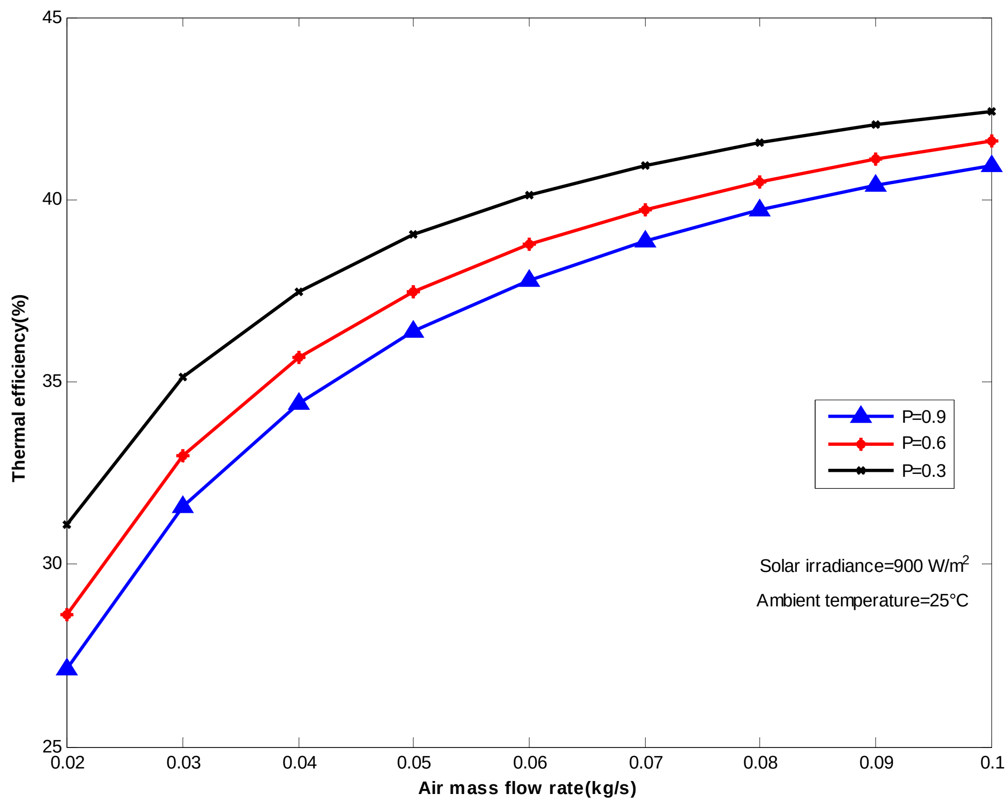

Fig. 7. Variation in the thermal efficiency with porosity and mass flow rate

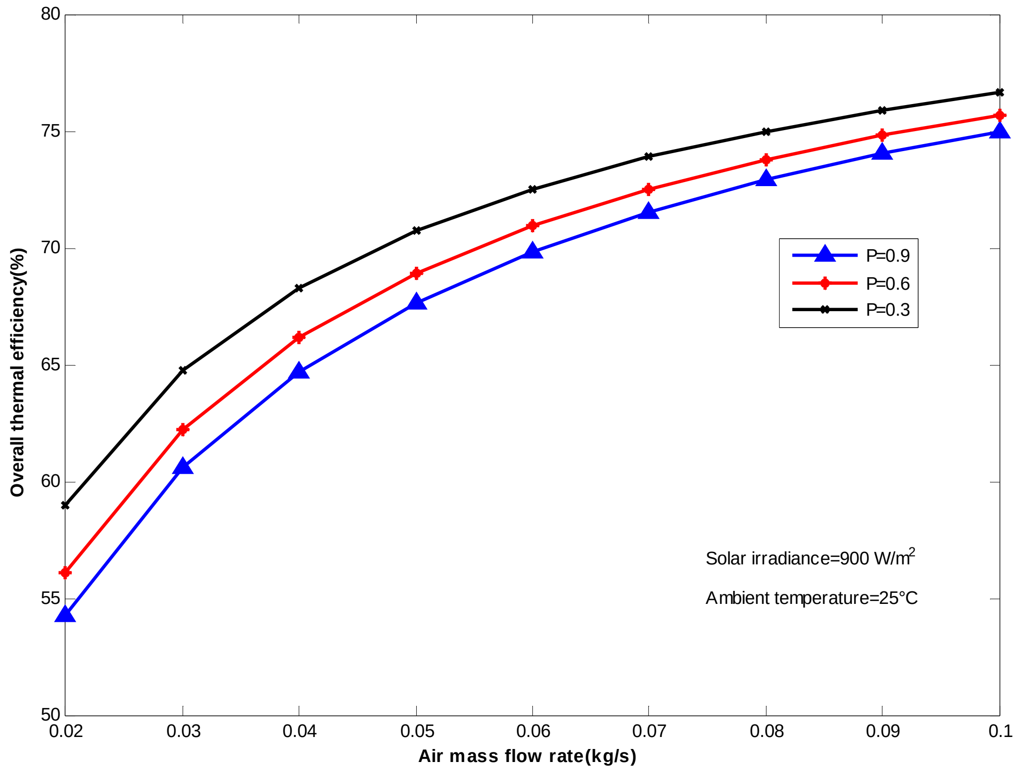

Fig. 8. Variation in the thermal efficiency for various mass flow rates and porosities

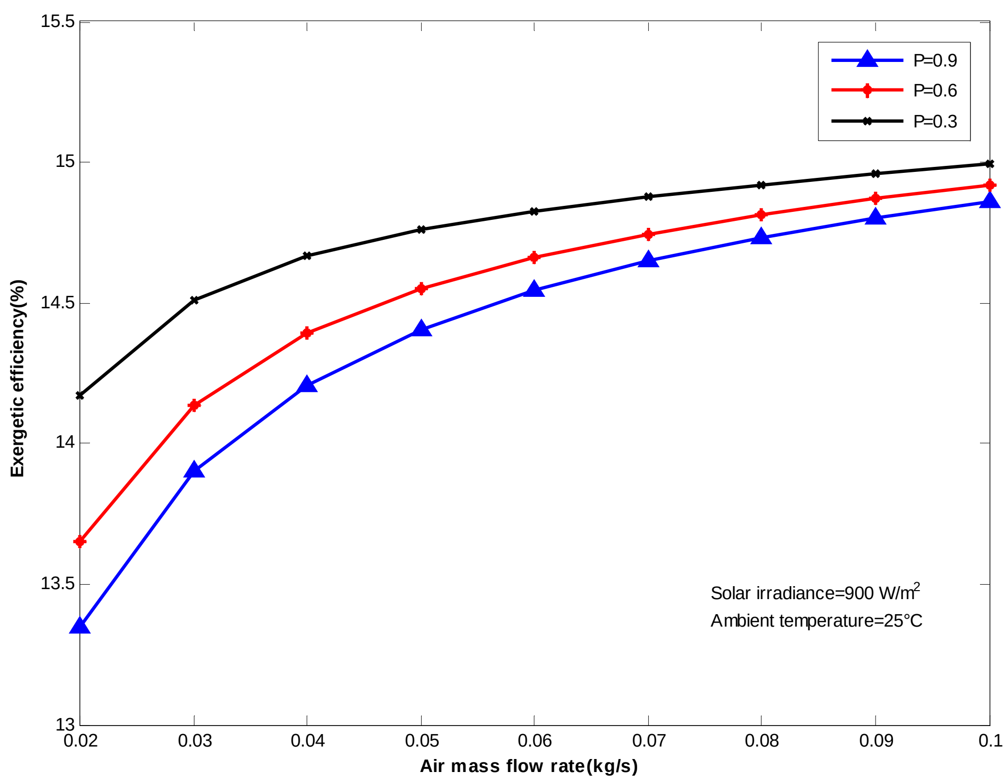

Fig. 9. Sensitivity of exergetic efficiency with respect to changes of mass flow rate and for values of porosity

From Fig. 9. The exergetic efficiency is plotted for different values of porosity and mass air flow. It can be noticed that, the increase of the air mass flow rate results a minimization of the entropy generation, which corresponds to a maximum exergetic efficiency. We also notice that the increase of exergetic efficiency is more significant when the mass flow rate changes from 0.02 to its typical value. This result is very clear when the porosity takes the value of 0.3. The typical value of the air mass flow rate ranges between 0.04 and 0.05 kg/s, after this value the increase of mass flow rate has little influence on the exergetic efficiency.

The exergetic efficiency decreased with increased porosity. This decline can be translated by the degradation of the produced energy quality. The highest exergetic efficiency is obtained for the lowest porosity.

6. Conclusion

In this work, an attempt has been made to show the effect of packing on the energy and exergy performances of double pass (PVT) air heater. The influence of porosity and mass air flow rate are also discussed. The following conclusions can be drawn:

- Using packing materiel plays a very important role in the enhancement of the convective heat transfer, which leads to reduce the temperature difference between the absorber plate and outlet air. Therefore the thermal and electrical efficiencies are significantly improved.
- Under the same conditions, the PVT system with packed bed provides higher exergetic efficiency.
- The overall thermal efficiency for system with packed bed is higher than that without packed bed by 11 to 13% throughout day.
- The energy and exergy performance are obtained for a low porosity.
- The increase of mass air flow rate results a maximization of the energy performance of the PVT air system with packed bed. For each value of porosity, there is a typical air mass flow rate. After this point the increase of exergetic efficiency of the system becomes very small.

Nomenclature

D	Diameter, m
w_1	width of upper air channel, m
w_2	width of lower air channel, m
T	Temperature, K
M	Air mass flow rate, kg/s
PF	Packing factor
P	Porosity
U_b	Bottom heat transfer coefficient, W/m^2 K
H	Heat transfer coefficient, W/m^2 K
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
I	Global solar radiation, W/m^2
e	Thickness, m
k	the thermal conductivity, W/m K
WPB	With packed bed
WTPB	Without packed bed
PV	Photovoltaic

Greek Symbols

η_{tex}	Total exergetic efficiency
η_{el}	Electrical efficiency
η_{t}	Overall thermal efficiency
η_{th}	Thermal efficiency
η_{ref}	Nominal efficiency
η_{elI}	Electrical efficiency improvement
η_{elWPB}	Electrical efficiency of system with packed bed
η_{elWTPB}	Electrical efficiency of system without packed bed
α	Absorbtivity
τ	Transmittance

Subscripts

ref	Reference value
fin	Air in inlet
fo	Air in outlet
f1	Air in upper channel
f2	Air in lower channel
ab	Absorber surface
g	Glass
i	Bottom
h	Hydraulic
w	Wind
a	Ambient
s	Sky
p	Packing material
rgs	Radiative glass to sky
rabg	Radiative absorber to glass
rabi	Radiative absorber to bottom
rabp	Radiative absorber to packing
rpi	Radiative bottom to packing
cgw	Convective glass to ambient
cgf1	Convective glass to air in upper channel
cabf1	Convective absorber to air in upper channel
cabf2	convective absorber to air in lower channel
cpf2	Convective packing to air
cif2	Convective bottom to air

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