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Improved PV/T solar collectors with heat extraction by forced or natural air circulation

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Abstract

The photovoltaic (PV) cells suffer efficiency drop as their operating temperature increases especially under high insolation levels and cooling is beneficial. Air-cooling, either by forced or natural flow, presents a non-expensive and simple method of PV cooling and the solar preheated air could be utilized in built, industrial and agricultural sectors. However, systems with heat extraction by air circulation are limited in their thermal performance due to the low density, the small volumetric heat capacity and the small thermal conductivity of air and measures for heat transfer augmentation is necessary. This paper presents the use of a suspended thin flat metallic sheet at the middle or fins at the back wall of an air duct as heat transfer augmentations in an air-cooled photovoltaic/thermal (PV/T) solar collector to improve its overall performance. The steady-state thermal efficiencies of the modified systems are compared with those of typical PV/T air system. Daily temperature profiles of the outlet air, the PV rear surface and channel back wall are presented confirming the contribution of the modifications in increasing system electrical and thermal outputs. These techniques are anticipated to contribute towards wider applications of PV systems due to the increased overall efficiency.

Keywords: PV/T collector; BIPV; Thermal energy; Air heater; Performance improvement

1. Introduction

The photovoltaic (PV) modules have been deployed to provide electricity in various types of buildings across the world and the recent development on photovoltaic/thermal

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Nomenclature

A_a	aperture area of PV module (m^2)
C_p	specific heat capacity ($J kg^{-1} K^{-1}$)
F_R	heat removal factor
G	solar irradiance ($W m^{-2}$)
I_{max}	maximum current at MPP (A)
$\dot{m}$	mass flow rate ($kg s^{-1}$)
P_{max}	maximum power at MPP (W)
T_a	ambient temperature (°C)
T_{in}	inlet air temperature (°C)
T_{pv}	PV module temperature (°C)
T_{out}	outlet air temperature (°C)
T_{ref}	reference temperature (25 °C)
U_L	overall loss coefficient ($W m^{-2} K^{-1}$)
U	loss factor ($W m^{-2} K^{-1}$)
V_{max}	maximum voltage at MPP (V)

Greek symbols

α	absorptivity
β	efficiency temperature coefficient (K^{-1})
η_{pv}	PV module efficiency
η_{ref}	reference efficiency
η_{th}	thermal efficiency
η_0	thermal efficiency for $T_{in} = T_a$
τ	transmissivity

(PV/T) concept offered an opportunity to increase overall efficiency by making use of waste heat generated in the PV module. It is well known that the efficiency of a PV solar cell decreases with an increase in the operating temperature and cooling is beneficial. PV cooling may be achieved by circulating a colder fluid, water or air, at its rear or front surface or both surfaces. In PV/T systems, solar thermal collectors are combined with PV cells to form hybrid energy-generating units that simultaneously produce the two types of energy required by most consumers, low temperature-heat and electricity. The absorbed solar radiation from the sun is partly converted to electricity by the PV cells and part of the excess heat generated in them is transferred to the heat exchanger in thermal contact with the PV cells while the rest is lost to the ambient. Like the thermal solar collectors, PV/T systems are categorized also according to the kind of heat removal fluid hence PVT/WATER and PVT/AIR are common types, for water and air heat removal fluids respectively.

In PV/T system applications, the production of electricity is the main priority and thus it is necessary to operate them at low temperatures to keep the PV module electrical efficiency at acceptable level. This requires the PV/T systems to be operated at low temperatures hence the extracted heat is suitable mainly for low temperature applications.

A number of experimental and analytical studies have been reported on PV/T systems and among the early works are on the concept of both water- and air-type PV/T collectors [1], the extension of the Hottel–Whillier–Bliss (HWB) model for analysis of PV/T systems [2], the detailed numerical models for both liquid and air PV/T systems [3] and a follow up computer simulation on the air-type PV/T system [4]. More recently, several experimental and theoretical studies on PVT/AIR systems based on the design and operating parameters, such as channel depth and mass flow rate, have been reported [5–7]. On the channel depth analysis for a single-pass PVT/AIR system, it has been suggested that the duct depth should be at least 10 cm for realistic results [8].

Air-cooled PV/T systems have been studied extensively mainly as an alternative and cost effective solution to building integrated PV (BIPV) systems. PV integration in the tilted roofs or façades or both of a building represents significant progress in urban solar application. In BIPV applications, an air gap between the module and the building fabric is used for circulating air to cool PV modules and the pre-heated air can be used for building thermal needs. The use of ventilated photovoltaic incorporating PV/T collector is a viable method of cost saving due to the combined provision of electrical power, heated air and hot water for use within the building [9] but need to adopt the 'holistic' approach to the building design to be cost effective [10]. Benemann et al. [11] and Bazilian et al. [12] gave elaborate built examples and research work on BIPV, demonstrating the elegancy of the PV/T systems, practical applications and developments. The air gap in a BIPV system behaves as a natural draft when no fan is used and the airflow is driven by buoyancy (heat) and the wind-induced pressure difference between the top and bottom of the gap. Substantial work, both theoretical and experimental, on the buoyancy-driven air movement behind PV panel for cooling has been reported [13–19]. These studies examined both the heat flow and airflow in an air channel behind the PV module and they reported low induced air velocities, less than $0.5\,\mathrm{m\,s^{-1}}$.

On the heat extraction using air on the commercial PV modules are referred the experimental works of Tripanagnostopoulos et al. [20] performed on prototype PV/T models built in the solar energy laboratory at University of Patras. Extensive research on PVT/AIR systems has been done in our laboratory, aiming at practical and efficient system configurations suitable to be used in PV installation in buildings. Most of the investigation focused on the effective heat extraction by forced airflow, applying simple (and cheap) heat extraction improvement modifications [21–23]. Recently we studied the use of a commercial PV module with air heat extraction as a roof solar collector for passive building ventilation in summer [24] and suggested the use of PVT/AIR systems in the agricultural [25] and industrial [26] sectors, introducing the concepts regarding these applications.

Several techniques for heat extraction improvements in the air channel exist and many of them involve the convectional air collectors. Among the methods is the use of fins [27], matrices [28], packed airflow passage [29] and porous or perforated plates for unglazed collectors [30]. The task of the present study is essentially the use of two modifications involving the interposing of a thin (flat) metallic sheet at the middle of the channel (TMS system) and attaching rectangular fins at the back wall of the channel (FIN system) to enhance heat transfer from the channel walls to airflow [21]. The choice of these techniques is based on their practicability, inexpensive and simplicity when incorporated into the building façade or roofs in the BIPV applications. We carried out outdoor experimental tests on two commercial PV modules configured as PVT/AIR solar collectors and run under forced and natural airflow modes. The steady-state thermal efficiency for the forced flow and the daily temperature profiles (for both flows) of the air outlet, PV module rear surface and back wall are presented. The paper focuses on the experimental study and as such presents experimental results regarding the relative performance improvement achieved by the modified systems with respect to the typical system. The analytical work with their generic results is not included in this paper, in view of the paper size and constitutes the subject of a paper to follow.

2. Experimental systems

Fig. 1 illustrates cross-sectional view of the air channels for the typical (referred as REF) and the modified (TMS and FIN) PVT/AIR systems. The REF system represents the typical single-pass air channel attached behind the PV module and is used as a datum system. The sheet in TMS creates a kind of double-pass configuration and doubles the heat extraction surface. The FIN system, on the other hand, consists of fins with rectangular profiles (Π) attached to the back wall of the air duct, for practical reasons and oriented parallel to the flow direction. Attaching them on the PV rear surface results in better PV cooling and increased heat production due to high PV temperature. In this case it requires incorporating the fins in the production phase of the PV module for good back thermal contact but makes it (PV) cumbersome, complex and heavy adding to the already high PV panel cost and transportation cost as well. In the suggested method, the locally fabricated fins may be fitted easily to the building façade or tilted roof making them cost effective. Both methods increase heat transfer from the channel walls to the circulating air but increase pressure drop (in the system).

Two identical prototype test models were constructed from two commercial pc-Si PV panels, of length 1 m, aperture area $A_a = 0.4\,m^2$ and rated 46 Wp, as 'absorber' plates and an air-channel of depth 15 cm attached at the rear surface of each module. The air channel casings were constructed from a thermal insulator board of thickness 5 cm on the backside and the edges with a thin aluminum sheet as inner lining. Small inlet and outlet vents of diameter 5 cm (to fit to the flexible tubes from the air pump) were provided at the top and bottom of the air channels, respectively. In order to improve PV module cooling, the channel surfaces, thin metallic sheet surface facing PV rear and the fins were painted black [14,22]. The fins height and spacing distance is each equal to 4 cm.

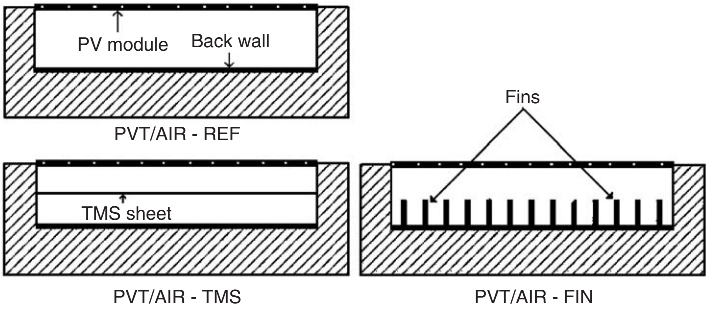

Fig. 1. Cross-sectional view of PVT/AIR collector models. Flow direction is perpendicular to the page.

The systems were mounted on a single mobile track at a tilt angle of 40° (approximate optimum tilt angle for Greece). During the experiments, two combinations of the three configurations (REF, TMS and FIN) were used at a time hence different test conditions are encountered for the three permutations. For forced flow experiments, the air circulation was effected through an air pump connected via a calibrated volumetric flow rate meter ($m^3 h^{-1}$) to the output vents through flexible air tubes. Experiments with different air inlet temperatures and flow rates were performed and steady-state efficiencies calculated. For the natural flow, the inlet and outlet vents were left open to have free-flow air circulation and inlet air temperature was equal to the ambient temperature. All the experiments were performed outdoor under clear sky conditions. The stagnation (with no airflow) experiments were also performed by sealing off the vents of the systems.

A number of thermocouples were used to measure the essential temperatures and their locations in the REF and TMS systems are illustrated in Fig. 2, left and right respectively. Type-T thermocouples were used for temperature measurements: PV module, T_{pv}, back wall, T_w, back insulation, T_b, ambient temperature, T_a (at secured location behind the systems) and the inlet, T_{in} and outlet, T_{out} air temperature. Thermocouples were also attached to the base of the fins in the FIN system, not shown in Fig. 2, in corresponding positions as that of the back wall. A Kipp & Zonen pyranometer was used to measure the in-plane insolation on the PV panel surface and a NRG40 anemometer recorded the wind speed. All the sensors were connected to CR10X (Campbell) data logger to record and store data. Resistive loads were connected across the PV output terminals to avoid the additional PV heating and to bias them at maximum power point. The delivery of the heat produced is not included in this study.

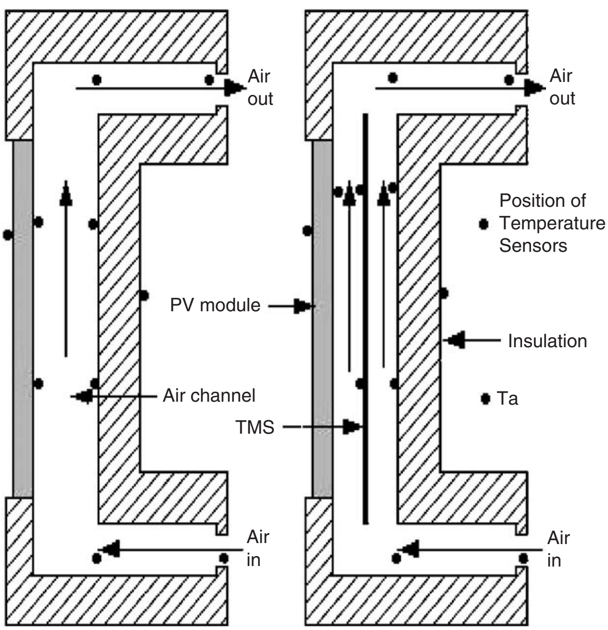

Fig. 2. Schematic diagrams showing temperature sensors position for REF (left) and TMS systems (right).

3. PV/T energy performance

In a PVT/AIR collector, the PV module captures the incident solar radiation and transmits a fraction of it to the airflow in the duct and the back wall in form of heat. The net radiation absorbed by the back wall surface raises its temperature as it gains more radiant heat energy from the rear surface of the PV module. The now heated back wall transfers some amount of this heat energy to the air circulation by convection and together with that from the PV rear surface contributes to air heating and result to higher outlet air temperature.

The PV electrical efficiency η_{pv} is known to decrease with the operating temperature of the module, T_{pv} and the linear correlation by Florschuetz [2] describes this behavior

$$\eta_{pv} = \eta_{ref}(1 - \beta(T_{pv} - T_{ref})), \tag{1}$$

where η_{ref} is the reference efficiency at the reference temperature, T_{ref} (25 °C) and β is cell efficiency temperature coefficient that can be determined experimentally.

The electrical efficiency was determined at regular time intervals in the course of experiments by disconnecting the load resistor temporarily and inserting a simple *I–V* circuit. The PV module electrical efficiency is calculated from the equation

$$\eta_{pv} = \frac{P_{max}}{A_a G} = \frac{I_{max} V_{max}}{A_a G}, \tag{2}$$

where P_{max} is the maximum power, A_a is the aperture area of the PV module and G is the incident solar radiation.

The PVT/AIR thermal efficiency can be described by the HWB equation [31] since its thermal part resembles that of the convectional solar thermal collectors

$$\eta_{th} = F_R \tau\alpha - F_R U_L (T_{in} - T_a)/G, \tag{3}$$

where F_R is the heat removal factor, τ is the transmissivity of front protective glass, α is the average absorptivity of the PV cells and substrate, U_L is the overall heat loss coefficient, T_{in} and T_a are the air inlet and ambient temperature, respectively.

Eq. (3) can be generalized for PV/T system by introducing the term η_0 which represent the thermal efficiency of the system when $T_{in} = T_a$ with electric power production:

$$\eta_{th} = \eta_0 - U\Delta T/G, \tag{4}$$

where $U = F_R U_L$ and $\Delta T = (T_{in} - T_a)$.

The thermal efficiency, η_{th} can be calculated from the equation

$$\eta_{th} = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_a G}, \tag{5}$$

where $\dot{m}$ is the air mass flow rate, C_p is the specific heat capacity of air and T_{out} is the air outlet temperature.

In Eq. (5), the mass flow rate in forced flow mode is controlled by the air pump and fixed throughout the experiment. Under outdoor tests, the airflow by natural convection in the channel depends on the weather conditions and is difficult to control it regarding stability and accurate measurements because of sporadic changes in weather conditions. We simulated the natural flow by performing forced flow experiments with a low flow rate from the pumping system (12.5 $m^3 h^{-1}$ or 4 $g s^{-1}$) so that the temperature rise to be close to those obtained with natural flow and used it to estimate airflow rate for the natural flow hence the relative efficiency.

4. Experimental results

The parameters that are essential for characterization of a PVT/AIR collector intended for BIPV applications are the PV module, T_{pv}, back wall, T_w and air outlet, T_{out} temperatures. The T_{pv} gives a measure of the ventilation effected by the thermal unit attached to the PV module with respect to unventilated PV module. The T_w is a measure of the shielding and cooling effect on the building as a result of PV module (or arrays) installation and airflow in the cavity, respectively. Finally, the T_{out} determines the thermal efficiency and ventilation rates (in case of natural flow). The results presented are for unglazed systems to avoid reduction of electrical output of the PV module due to reflection and absorption losses of the additional glazing and to avoid high temperatures which may subject the PV module to thermal stresses with possible detriment to the module life.

4.1. PV module electrical efficiency

The electrical efficiency is presented in Fig. 3 as a function of the PV module temperature where the electrical efficiency is seen to drop with the rise in PV module temperature as expected. The linear correlation between the electrical efficiency and the module temperature is described by the linear curve in Fig. 3 and the linear equation describing it is given by

$$\eta_{pv} = 0.147 - 0.0008\, T_{pv}. \quad (6)$$

Note that Eq. (6) can be translated to take the accepted form of Eq. (1) as follows:

$$\eta_{pv} = 0.127(1 - 0.0063(T_{pv} - 25)), \quad (7)$$

where $\eta_{ref} = 0.127$ at $T_{ref} = 25^\circ$ (the standard temperature) and $\beta = 0.0063\,\mathrm{K}^{-1}$.

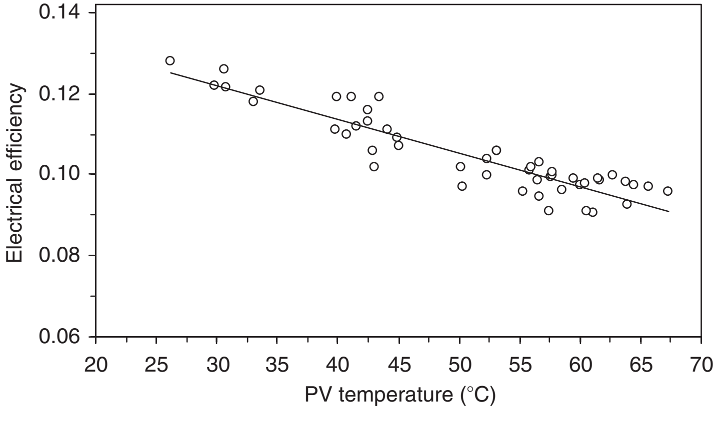

Fig. 3. Electrical efficiency as a function of PV temperature.

4.2. Thermal efficiency for the forced flow

In Fig. 4, the variation of thermal efficiency with flow rate is given and all the systems display similar trend where the thermal efficiency increases exponentially with the flow rate. Looking at the results in Fig. 4, one notices at once that the FIN system has higher thermal efficiency, followed by the TMS system and lastly the REF system for the entire flow rates. Thus, the modifications increase thermal efficiency hence more heat production for meaningful applications.

In Fig. 5, the steady-state thermal efficiency η_{th}, obtained at different air inlet temperature, is plotted against $\Delta T/G$ (with $\Delta T = T_{in} - T_{a,}$ with flow or $\Delta T = T_{pv} - T_a$ under stagnation). The linear curves in Fig. 5 are summarized by the equations in Table 1. From Table 1, one notices that the maximum thermal efficiency that can be achieved by the REF, TMS and FIN system from these experiments are 25%, 28% and 30%, respectively. Thus

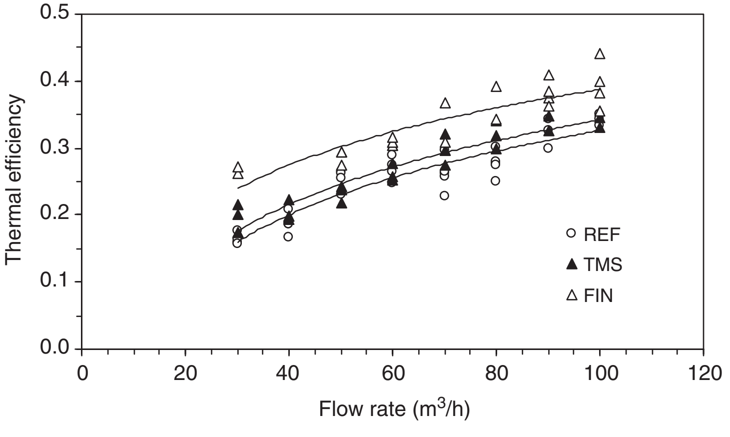

Fig. 4. Influence of airflow rate on thermal efficiency.

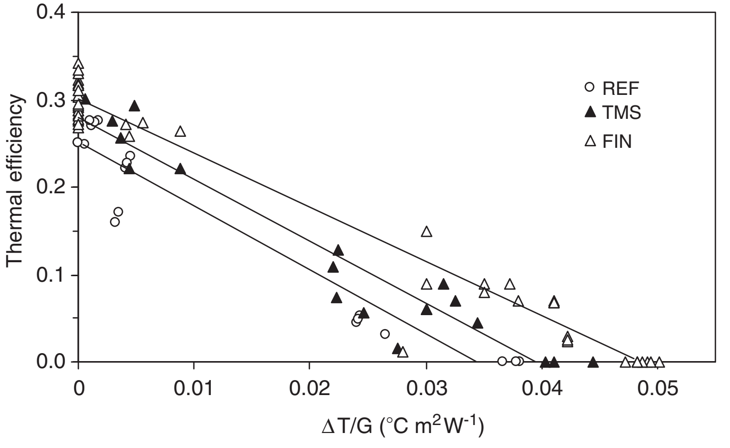

Fig. 5. Thermal efficiency as a function of $\Delta T/G$.

the results show that the FIN system has higher thermal efficiency, followed by the TMS and lastly the REF system with efficiency improvement of upto 12% and 20% for TMS and FIN system, respectively. Note that these are the thermal curves obtained with the electrical production.

4.3. Daily temperatures

The Figs. 6–11 presents the typical daily profiles of the essential temperatures of the PVT/AIR systems together with the ambient temperature T_a and solar radiation G with system orientated due south. Each graph gives results for two system combinations performed on the same day i.e. either REF and TMS or REF and FIN or TMS and FIN. Figs. 6–8 and Figs. 9–11 give the results obtained with the forced and natural flows, respectively.

4.3.1. Forced air flow

Fig. 6 presents the results obtained for the REF and TMS systems and shows that the TMS system has slightly lower PV temperature and lower back wall temperature and slightly higher air outlet temperature than the REF system. Fig. 7 gives the results for the REF and FIN systems and shows that the FIN system has slightly lower PV temperature and lower back wall temperature and higher air outlet temperature than the REF system. Fig. 8 shows the results for TMS and FIN systems where the FIN system has lower PV

Table 1
Linear equations describing the curves in Fig. 5

PV/T system type	Equation
PVT/AIR-REF	$\eta_{th} = 0.25 - 7.31\Delta T/G$
PVT/AIR-TMS	$\eta_{th} = 0.28 - 7.14\Delta T/G$
PVT/AIR-FIN	$\eta_{th} = 0.30 - 6.14\Delta T/G$

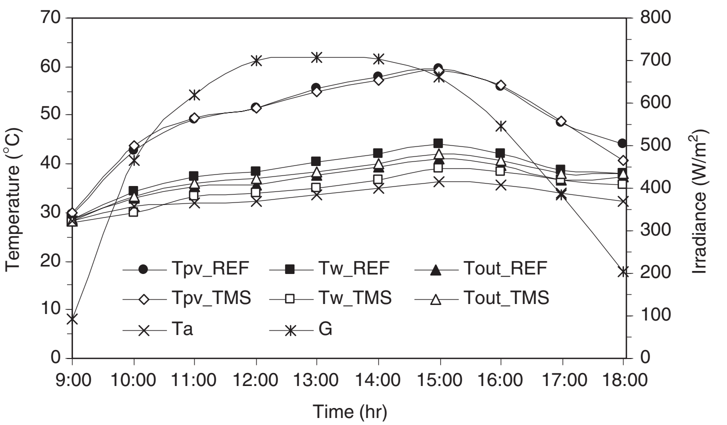

Fig. 6. Forced airflow daily temperature profiles for REF and TMS systems.

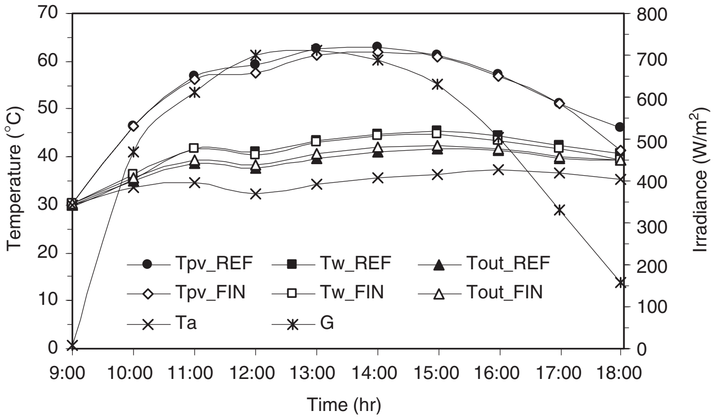

Fig. 7. Forced airflow daily temperature profiles for REF and FIN systems.

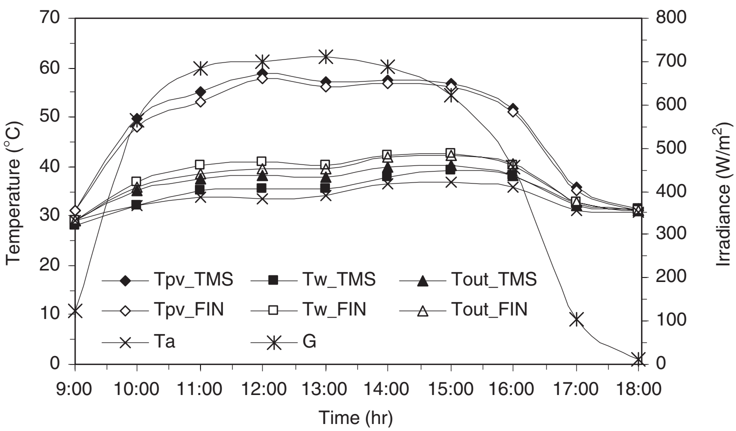

Fig. 8. Forced airflow daily temperature profiles for TMS and FIN systems.

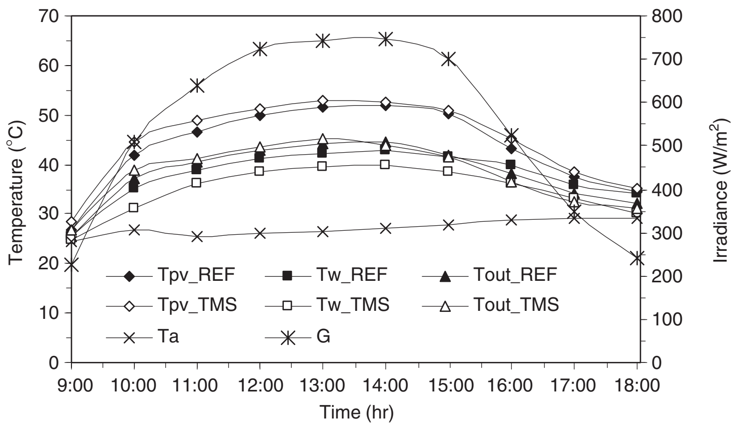

Fig. 9. Natural airflow daily temperature profiles for REF and TMS systems.

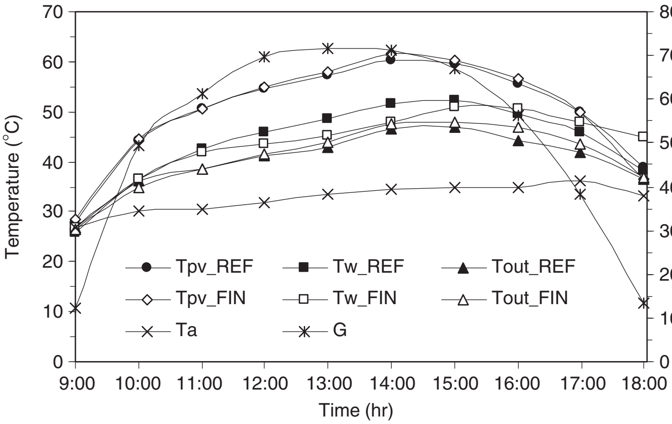

Fig. 10. Natural airflow daily temperature profiles for REF and FIN systems.

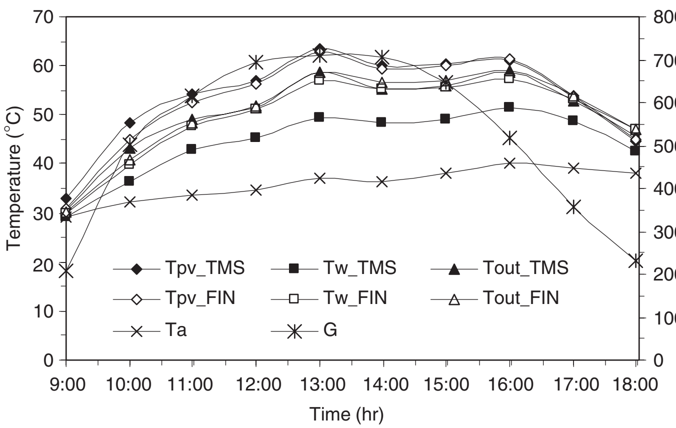

Fig. 11. Natural airflow daily temperature profiles for TMS and FIN systems.

temperature, higher back wall temperature and higher air outlet temperatures than the TMS system.

4.3.2. Natural air flow

The results for natural flow (Figs. 9–11) follow similar trends as those of forced flow. In all experiments, the TMS system presents lower back wall temperature than the REF and FIN systems while the FIN system presented slightly higher output temperature (or efficiency) than the other two systems. For the simulated flow rate of $12.5\,m^3\,h^{-1}$, the obtained thermal efficiency at noon is about 16%, 18% and 20% for REF, TMS and FIN system, respectively.

5. Discussion

The electrical efficiency reduces with PV module temperature and the suggested modifications increase the thermal efficiency of the PVT/AIR collectors by 12% and 20%

for TMS and FIN systems, respectively compared to the REF system for both airflow modes. In forced flow mode and airflow rate of $60\,m^3\,h^{-1}$ the corresponding air velocity is $0.25\,m\,s^{-1}$ while for natural flow with the simulated flow rate of $12.5\,m^3\,h^{-1}$ the corresponding air velocity is $0.06\,m\,s^{-1}$. We measured the air velocity using a hot-wire anemometer at various points in the channel and found the values to fluctuate haphazardly upto to $0.4\,m\,s^{-1}$, varying with position within the channel and for accurate measurements other methods [15,17] could be employed.

The module temperature measured with no air circulation (i.e. under stagnation) for all the PVT/AIR configurations was about 55–75 °C at ambient temperature of about 30 °C or more and insolation level of 700–800 $W\,m^{-2}$. With the air circulation, the measured PV module temperatures range from 45 to 65 °C depending on the flow rate, weather conditions and time of the day. Thus the air circulation by forced or natural flow in the air channel reduces the PV module temperature by at least 5 °C and thus may contribute to improve electrical output power. Looking at the daily PV module temperature profiles presented in Figs. 6–11, the PV temperature increases as solar insolation increases and the modifications are more effective in ventilating the PV module for forced flow but for natural flow there is a marginal benefit as compared with the reference system.

The modifications lowers the back wall temperature compared to the REF system with the TMS system giving lower values than the FIN system for both natural and forced flows and contribute to reduce the building overheating by the conduction heat gain through the building's wall or roof materials. The TMS system presents lower values since the metal sheet 'shields' the back wall from 'seeing' directly the rear surface of the PV module hence lower radiation heat exchange between them. For the FIN system, the fins enhance heat transfer from the back wall to airflow resulting to its lower temperature than that of the REF system but its direct 'view' on the rear surface of the PV module makes it attain higher wall temperature than TMS system due to more heat exchange. Closer inspection of the temperature profiles in the Figs. 6–11, one notices that the thin metal sheet reduces the back wall temperature by upto about 5–3 °C for forced and natural flow, respectively while the fins reduce the back wall temperature by about 2 °C for both forced and natural flow.

The modified systems give higher outlet air temperature with respect to REF system for both forced and natural flow with the FIN system having higher value than the TMS system. In the FIN system, heat is conducted along the fin from the base towards the tip and simultaneously the fin dissipates heat by convection to the flowing air and increases the rate of heat convection in the channel generally through cascaded effect. The rate of heat dissipation from the finned back wall to the flowing air increases and tends to lower the back wall temperature which in turn promotes the radiative heat transfer from the PV module rear surface to the back wall. The net result is to boost the outlet air temperature and lowering of PV module temperature. In the TMS system, the sheet doubles the heat transfer surface area hence enhance convection heat transfer to the airflow and creates two channels. The upper channel (between TMS and PV rear surface) attains higher outlet temperature due to the high PV and TMS temperature but the lower channel (between TMS and back wall) with low back wall temperature attains low outlet temperature resulting in overall reduced outlet temperature than the FIN system but higher than the REF system due the doubled surface area. Thus the FIN system is more effective in PV cooling and heat extraction than the TMS and REF systems while the TMS is superior in reducing the back wall temperature than the REF and FIN.

The pressure drop for the three configurations are found to be less than 10 Pa for the flow rate of $60\,m^3\,h^{-1}$ with TMS giving higher pressure drop than FIN system. Considering 80% overall efficiency for the pump and motor, the respective pumping powers were calculated as 177.7, 178.3 and 178.2 mW for REF, TMS and FIN systems, respectively. We observe that the pumping powers for the three configurations are generally small and in agreement with the simulation results presented by Choudhury and Garg [29]. The additional power required by the modified systems are 0.537 and 0.506 mW for TMS and FIN systems, respectively and the typical power produced by the PV modules used is about 35 W, hence the additional power is negligible (less than 1%) to degrade its electrical output power by appreciable amount. Further, the increased electrical efficiency by the improved cooling may compensate the additional power required and the increased thermal efficiency is an additional benefit making the modifications cost effective in energy production and operation. The results in Ref. [29] show that for doubled channel length or halved duct depth, the necessary pumping power increases by about 10 times. For the BIPV applications with typical length of about 5–10 m, the 15 cm can be considered a balance depth regarding thermal performance and pressure drop as the net electrical output is kept at acceptable level due to low electricity input for the pump (fan) load.

The modified systems contribute significantly to the energy saving in the buildings because of the increased overall efficiency. The heat produced can be channeled through proper ducting system into the building interior or exterior for heating and cooling (ventilation) in winter and summer, respectively. The ventilation of a building is either to control the indoor air quality or temperature (avoidance of overheating) in summer and a PVT/AIR collector can fulfilled these two functions satisfactorily. The suggested modifications and their mounting are practical in that they can easily be fabricated and attached in the building structure considering that the off-the-shelf modules are to be used. The system, when operated in free flow mode, can provide year round thermal comfort with good user control at minimum capital cost and negligible operation and maintenance hence cost effective. The improved PVT/AIR system can be used also to heat air for several industrial or agricultural processes, such as drying of products, and could promote PV applications in these sectors.

6. Conclusions

The possibility of generating electricity and heat energy from a commercial PV module adopted as a PVT/AIR solar collector with either forced or natural airflow in the channel was demonstrated. Under natural flow, the temperature rise could reach upto about 12 °C in the early afternoon during sunny days and could induce sufficient airflow rate to effect adequate ventilation. For the forced convection with flow rate of $60\,m^3\,h^{-1}$ and 15 cm channel depth, the use of fins yields an efficiency of 30% followed by the thin metallic sheet with 28% and lastly the typical with 25% for our models and thus the suggested modifications yield higher thermal efficiency than the normal system, with better electrical performance due to the achieved PV cooling. The FIN type system gives higher thermal output than TMS system. Both modified systems have lower back wall temperature compared to the reference system with the TMS system presenting lower value due to the additional shading effect of the suspended metallic sheet and helps to reduce conduction heat gain by the building through the building fabric. The choice of the modification depends on the location of application which determines the optimization of the PVT/AIR collector required, whether for heating or cooling. In high latitude regions, heating in winter is more emphasized than cooling in summer while the converse is true for low latitude and tropical regions. In such scenarios, use of FIN system is ideal for high latitude regions (more heating) where the high heat gain is exploited in winter whereas in low latitude and tropical countries (more cooling), the TMS is suitable to maximize both the improved heat gain as well as its additional wall shading effect. Therefore, the increased performance of the modified PVT/AIR systems will contribute immensely towards wider application of PV systems and mitigation of energy supply of buildings and consequently lower CO_2 emission among other social benefits.

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