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Performance Study of Air-based Photovoltaic-thermal (PV/T) Collector with Different Designs of Heat Exchanger

(Kajian Prestasi Pengumpul Fotovoltan-terma (PV/T) Berasaskan Udara dengan Beberapa Reka Bentuk Penyerap Haba)

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ABSTRACT

Three different designs of heat exchanger, V-groove, honeycomb and stainless steel wool had been tested to study their effectiveness in improving the overall performance of a photovoltaic/thermal (PV/T) air base solar collector. Heat exchangers were installed horizontally into the channel located at the back side of the PV module. The system was tested at irradiance of 828 W/m² with mass flow rate spanning from 0.02 kg/s to 0.13 kg/s. It was observed that at mass flow rate of 0.11 kg/s, the maximum thermal efficiency of the system with V-groove is 71%, stainless steel wool is 86% and honeycomb is 87%. The electrical efficiency of the systems is 7.04%, 6.88% and 7.13%, respectively. The experimental results showed that honeycomb design is the most efficient design as heat exchanger. The design which is simple and compact is suitable for building integration.

Keywords: Electrical efficiency; heat exchanger; photovoltaic/thermal; thermal efficiency

ABSTRAK

Tiga penyerap haba dengan reka bentuk yang berbeza iaitu lengkuk-V, sarang lebah dan serabut keluli tahan karat telah diuji untuk mengkaji keberkesanannya bagi menambahbaik prestasi keseluruhan pengumpul fotovoltan terma (PV/T) berasaskan udara. Kesemua penyerap haba dipasang secara selari ke dalam ruang bawah modul fotovoltan. Sistem telah diuji pada keamatan sinaran 828 W/m² dan kadar aliran jisim udara 0.02 kg/s hingga 0.13 kg/s. Didapati, pada kadar aliran jisim udara 0.11 kg/s, maksimum kecekapan terma untuk sistem dengan lengkuk-V adalah 71%, sarang lebah 86% dan serabut keluli tahan karat 87%. Manakala kecekapan elektrik pula adalah 7.04%, 6.88% dan 7.13% masing-masing. Keputusan uji kaji merumuskan bahawa penyerap haba berbentuk sarang lebah adalah reka bentuk penyerap haba yang paling cekap. Reka bentuknya ringkas dan padat serta sesuai untuk diintegrasikan ke dalam bangunan.

Kata kunci: Fotovoltan/terma; kecekapan elektrik; kecekapan terma; penyerap haba

INTRODUCTION

Solar energy is the cheapest and cleanest source of energy which is readily available in this world. Over the years, many researches and commercial activities have been carried out to utilize the solar energy. Technologies toward harvesting solar energy can be divided into three main applications namely; solar thermal, solar photovoltaic and solar photovoltaic/ thermal. This study will focus on photovoltaic/thermal technology.

For most developing countries, agriculture activities are located in remote villages and rural areas. Due to economic factors, the activities experience difficulties in connecting the drying systems to the national grid. The same problem occurs for rural consumers to get sufficient electricity, hot water and hot air for domestic utilities. Therefore the concept of using photovoltaic/thermal solar collector has been introduced. A photovoltaic thermal solar collector is a combination of photovoltaic panel (PV) and solar thermal components or system which is capable of producing both electricity and thermal energy simultaneously in one integrated system.

The concept of PV/T system has been studied, discussed and published for almost 4 decades now. Both water and air are suitable to be used as the cooling fluid to cool the PV module in order to avoid the drop of electrical efficiency. However air based PV cooling system is more simple and economical due its minimal usage of material and low operating cost. A high thermal conductivity material together with natural or forced flow of air located at the back of the PV module shall remove the heat through convention and conduction heat transfer. Review papers on PV/T collectors has been written by Hasan and Sumathy (2010), Kumar and Rosen (2011) and Tiwari et al. (2011).

A comparison study of four models of PV/T collector has been carried out (Hegazy 2000). Both single pass and double pass system has been evaluated. Heat balance equation has been identified and solved for each model.

For the best model, the overall efficiency is 55% at specific mass rate of 0.04 kg/sm^2. The performance of a double pass PV/T solar collector suitable for solar drying system has been investigated (Sopian 2000). Firstly, the air will flow at the channel between the glass cover and the PV panel and then it will flow through the second channel between the PV panel and the back plate. This flow arrangement increases the heat removal and reduces heat loss.

A study on nine different design concepts of combined PV/T water and air solar collector system has been carried out (Zondag et al. 2003). The design concepts have been divided into four different groups. Two types of PV panel has been investigated namely; the conventional opaque PV panel and the transparent PV panel. The results showed that 52% thermal efficiency has been achieved for an uncovered PV/T collector, 58% for single cover sheet-and-tube design and 65% for typical channel above PV design. Another study was on two low cost improvement design of heat remover placed in a channel of a PV/T system (Tonui & Tripanagnostopoulos 2007). The improved design involved was done by introducing a thin metal sheet and fin attached to the back wall of the channel. Both metal sheet and fin were fabricated locally using available cheap material.

A performance study on a double pass air base PV/T system with fins attached at the back of the absorber plat of the PV module was also carried out (Othman et al. 2007). The experiment showed that by using fins as the integral part of the PV module increases the overall efficiency of the system. The thermal efficiency of the double pass PV/T system with porous media at the lower channel has been evaluated by Sopian et al. (2009). The experimental results proved that by introducing the porous media at the lower channel has increased the heat transfer area which leads to the increase of the thermal efficiency of the system from 60 to 70%. The designed system is suitable for drying applications.

Further research work has been carried out to study the performance of a single pass PV/T system with aluminum ∇- grooved absorber plate (Othman et al. 2009). Aluminum with thickness of 0.7 mm was attached to the back of the PV module. The results showed that the electrical efficiency was improved by 1% and the thermal efficiency increased by 30%. Another study was carried out to evaluate the performance of a single pass air base solar collector with rectangular tunnel heat exchanger (Jin 2010). The material of the rectangular tunnel is also made of aluminum. The results showed that the PV/T system with tunnel has a better performance compared with the conventional PV/T. The electrical efficiency and thermal efficiency were found to be 10.02% and 54.70%, respectively, at irradiance of 817.4 W/m^2 and mass flow rate of 0.0287 kg/s.

In this work, a single pass air base photovoltaic/ thermal (PV/T) solar collector combined with various heat exchangers has been studied. In order to remove the heat from the back of the PV module, three different designs of heat exchanger, V-groove, honeycomb and stainless steel wool were installed horizontally into the channel located at the back side of the PV module. Under similar set-up of operational condition, each heat exchanger was tested one by one to observe its performance.

EXPERIMENTAL DESIGNS OF PV/T COLLECTORS

The performance of each PV/T solar collector has been tested indoor using a laboratory fabricated solar simulator (Hussain et al. 2011). Each PV/T collector was installed with heat exchanger in order to improve its overall performance. Three different designs of heat exchanger, V-groove, honeycomb and stainless steel wool were installed horizontally into the channel located at the back side of the PV module (Hussain et al. 2012). Under similar set-up of operational condition, the system was tested one by one at irradiance of 828 W/m^2 with mass flow rate span from 0.02 kg/s to 0.13 kg/s.

Figure 1 shows the photograph of the fabricated PV/T solar collector. It is a single pass system with air as the

FIGURE 1. The fabricated PV/T solar collector

medium for heat transfer. The same testing system was used to compare the performance of all designs of heat exchanger.

The first design of the PV/T collector is shown in Figure 2 (Hussain et al. 2012). It is a collector with honeycomb heat exchanger. Locally purchased aluminum sheet has been made into corrugated sheet. The thickness of the sheet is ~ 0.2 mm. Five pieces of aluminum corrugated sheets as shown in Figure 3 were joined together to fabricate a piece of compact honeycomb with hexagonal geometry. The honeycomb was installed horizontally into the channel located at the back side of the PV module as shown in Figure 4.

Figure 5 illustrates the second design of the PV/T collector with V-groove heat exchanger. V-groove is fabricated using locally purchased aluminum sheet. The thickness of the aluminum sheet is ~ 0.5 mm. The V-groove was installed at the back of the PV module using same method as in Figure 4.

Finally, the third design of the PV/T collector is shown in Figure 6. The heat exchanger chosen was locally purchased stainless steel wool. The stainless steel wool has been tested to prove that it will not rust over time. The stainless steel wool was attached to a piece of aluminum sheet. The complete design was installed to the back of the PV module using the same method as shown in Figure 4.

The effectiveness of PV/T collector with each design of heat exchanger was studied to identify their overall performance. The performance of the collectors were evaluated and compared in terms of its electrical and thermal efficiencies.

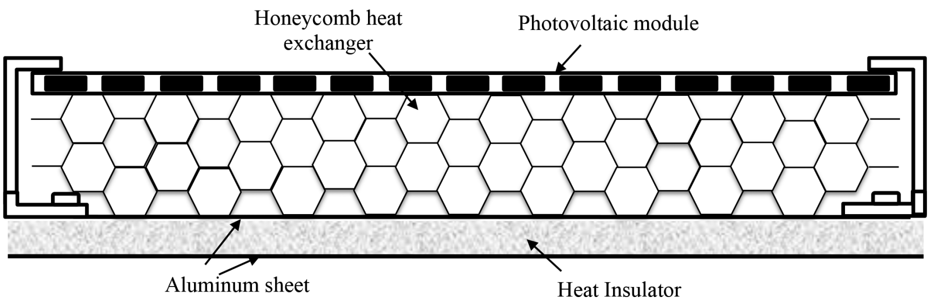

FIGURE 2. PV/T collector with honeycomb heat exchanger

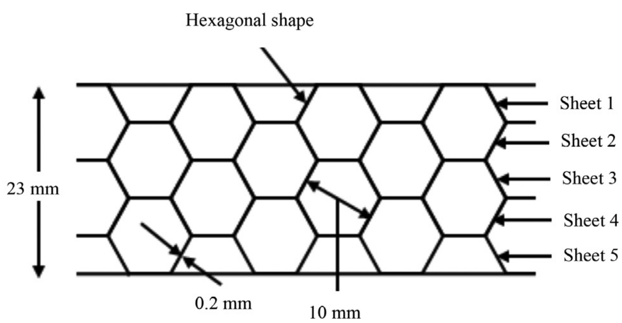

FIGURE 3. Joined aluminum corrugated sheet

FIGURE 4. Honeycomb installed at the back of PV module

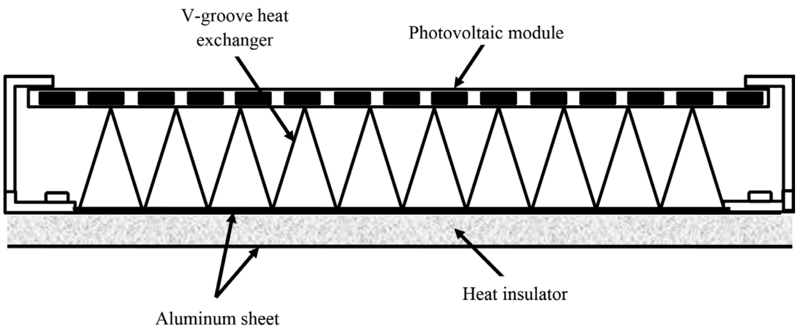

FIGURE 5. PV/T collector with V-groove heat exchanger

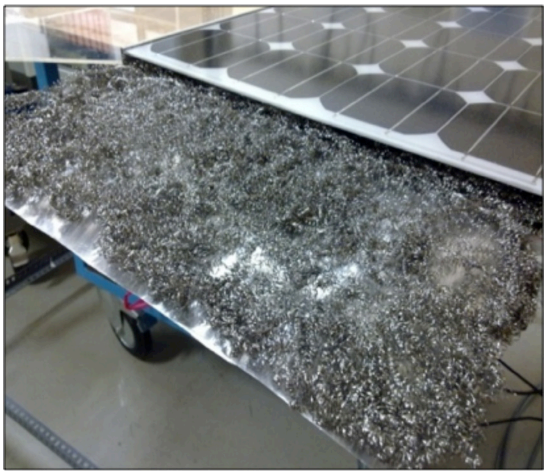

FIGURE 6. PV/T collector with stainless steel wool heat exchanger

EXPERIMENTAL SET-UP

The aim of this experiment was to develop an efficient PV/T solar collector. The electrical efficiency of PV module operated at high temperature above 25°C shall be maximized and at the same time, collect and utilize the thermal energy from the design system. Therefore three different designs of heat exchanger: V-groove, honeycomb and stainless steel wool located at the back of the PV module has been tested in the experiment.

The fabricated system of PV/T solar collector is shown in Figure 1. A mono-crystalline (SolarWorld, SW 85) photovoltaic module was used to harvest the electrical energy. The thermal system consists of a blower attached into a galvanized ducting with length of 2.5 m. A voltage regulator had been used to control the air speed of the blower between 0.4 m/s to 1.5 m/s flow through the system. A heater controlled by a voltage regulator was installed into the ducting in order to ensure that the inlet temperature is equivalent to the ambient temperature.

Ten units of type-T thermocouples were placed at various locations of the system. Inlet temperature, panel temperature, outlet temperature and temperature at the back of the thermal insulator were measured and used to calculate the thermal efficiency of the system. First, the PV/T collector system efficiency was studied without any heat exchanger installed into the system. Then the system efficiency was tested with the honeycomb heat exchanger, followed by the V-groove and finally with the stainless steel wool.

During the experiment, air with mass flow rate spans from 0.02 kg/s to 0.13 kg/s flows through the heat exchanger. Polyethylene has been used to cover the ducting and the back of the PV module as thermal insulation to minimize heat loss from the system. Three units of fans were used to minimize the effect of infrared from the halogen lamps of the solar simulator.

EXPERIMENTAL PROCEDURE

The comparison study has been separated into four parts with similar set-up of operational condition namely set-up of; without any heat exchanger, honeycomb, V-groove and stainless steel wool. For all parts, the performance of the PV/T system had been tested with irradiance setting of 828 W/m^2 at 5 different mass flow rates. The mass flow rates of the air through the system were set to 0.021 kg/s, 0.042 kg/s, 0.085 kg/s, 0.110 kg/s and 0.128 kg/s.

At each mass flow rate setting, time of not less than 70 min was allowed for temperature stabilization. The measurements of short circuit current, I_{sc} (A), open circuit voltage, V_{oc} (V), maximum current, I_m (A) and maximum voltage, V_m (V) were measured using Agilent 34401A digital multimeter. The irradiance value was measured using LICOR pyranometer. Equation (1) is used to calculate the electrical efficiency of a PV/T system. The measurements of short circuit current, I_{sc} (A), open circuit voltage, V_{oc} (V), can be done by direct connection between the multimeter and the PV module.

$$\pi_{et} = \frac{I_m \times V_m}{Ac \times s} \times 100\%. \tag{1}$$

The maximum current, I_m (A) and maximum voltage, V_m (V) were determined from I/V curve measurement of the PV module using digital multimeter and rheostat. A_c is the area of the solar cell and S is the average irradiance value during the experiment.

Inlet temperature, T_i, panel temperature, T_s, outlet temperature, T_o and temperature at the back of the thermal insulator, T_b were measured and used to calculate the thermal efficiency of the system. The mass flow rate, m of the air flow through the system was calculated using (2).

$$m = \rho A V_{av}. \tag{2}$$

The mass flow rate of fluid is important to calculate the thermal efficiency of the system. For temperature below 100°C, density of air ρ is considered constant. A is area of input. Speed of air from blower through the ducting was regulated using voltage regulator. Then air velocity, V_{av} at input location was calculated. Equation (3) was used to calculate the thermal efficiency of the developed PV/T system.

$$\pi_{th} = \frac{mc_p\left(T_o - T_i\right)}{A_p S} \times 100\%. \tag{3}$$

C_p is specific heat of air, A_p is the area of the PV/T collector, T_i is the temperature air at input location and T_o is the temperature air at output location of the system and S is the average irradiance value during the experiment.

Results and Discussion

Three different designs of heat exchanger namely the honeycomb, V-groove and stainless steel wool were installed separately into the PV/T collector. The aim of the experiment was to investigate the capability of each heat exchanger to enhance the thermal efficiency and the electrical efficiency of the PV/T system. All parameters involved in the calculation of thermal and electrical efficiency were measured in details.

In theory, the larger the surface area of heat exchanger touching the back of the PV module, the better the heat transfer from the back of the PV module into the moving fluid (Roslan et al. 1998). The mass flow rate of the moving fluid also plays an important role. The heat will transfer through radiation, convention and conduction. For each PV/T system, the difference between the output temperature and input temperature was compared. Figure 7 shows the temperature difference, (T_o – T_i) °C for all types of heat exchanger at irradiance of 828 W/m^2.

For all type of heat exchanger, the temperature difference decrease with the increase of the mass flow rate. The results showed that PV/T collector installed with heat exchanger is capable to absorb more heat compared with PV/T collector without heat exchanger. At mass flow rate of 0.11 kg/s, the temperature difference of PV/T collector with honeycomb and stainless steel heat exchanger gives almost similar results ~ 4.0°C. The PV/T system with V-groove gives results of 3.3°C and for system without any heat exchanger; the temperature difference is 1.3°C. The results showed that PV/T collector with honeycomb and stainless steel heat exchangers were capable to absorb heat more efficiently.

Figure 8 shows the plot of the electrical efficiency for all collectors. Overall, all types of heat exchanger show an increasing trend for electrical efficiency, with the increase

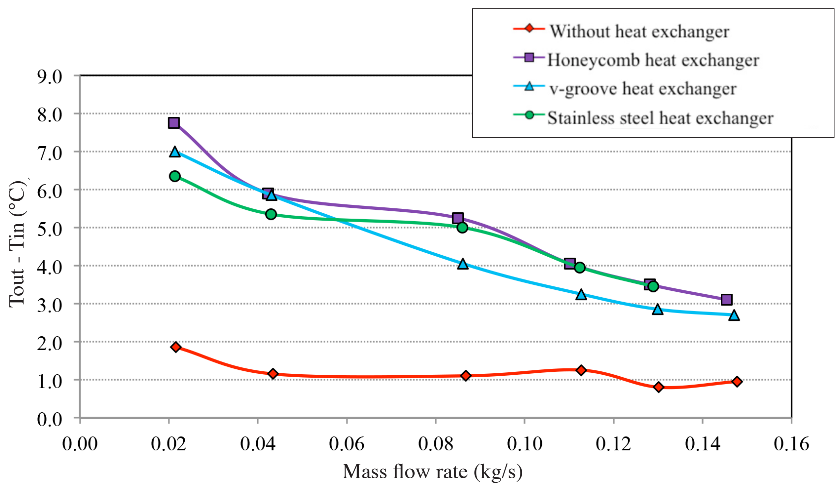

FIGURE 7. Temperature difference, (T_o – T_i)°C

of the fluid mass flow rate except for the stainless steel wool heat exchanger. The structure of the stainless steel wool is not uniformed to allow air to flow freely through it from inlet to outlet. The structure resistance caused a pressure drop to the flowing air. The result proved that stainless steel wool is not suitable to be used to remove heat from the back of the PV module. PV/T collector with honeycomb heat exchanger shows slightly higher electrical efficiency, compared with other collectors.

Figure 9 shows the thermal efficiency, for all collectors at 828 W/m^2. The experimental result showed that the thermal efficiency increases with the increase of mass flow rate up to 0.11 kg/s. Above mass flow rate of 0.11 kg/s, the thermal efficiency remains stable. The maximum thermal efficiency of the collector with the honeycomb and stainless steel wool is ~ 87%. PV/T collector with V-groove heat exchanger gives 71% maximum thermal efficiency. The maximum thermal efficiency of PV/T without any heat exchanger is only 27%. The result showed that the structure of honeycomb and stainless steel wool with large surface area touching to the back of the PV module is capable to enhance the heat transfer from the back of the PV module to the air as the moving fluid.

Referring to the experimental results, each type of heat exchanger performs differently. The aim of the experiment was to investigate the capability of each heat exchanger in enhancing the thermal efficiency and the electrical efficiency of the PV/T system. The honeycomb PV/T system and stainless steel wool PV/T show similar results for the thermal efficiency. However the honeycomb PV/T system shows better result for electrical efficiency. The results from this experiment were compared with other previous works for similar collector system and it was found that the improvement is mainly in thermal efficiency. Therefore, findings from this experiment can be further improved and implemented in the near future.

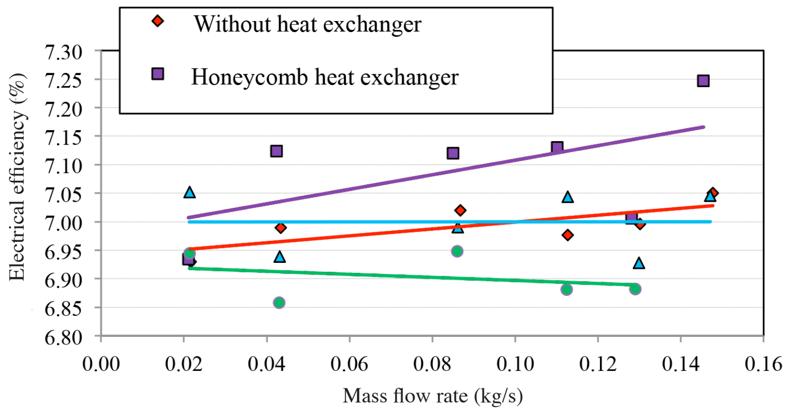

FIGURE 8. Electrical efficiency, for all collectors

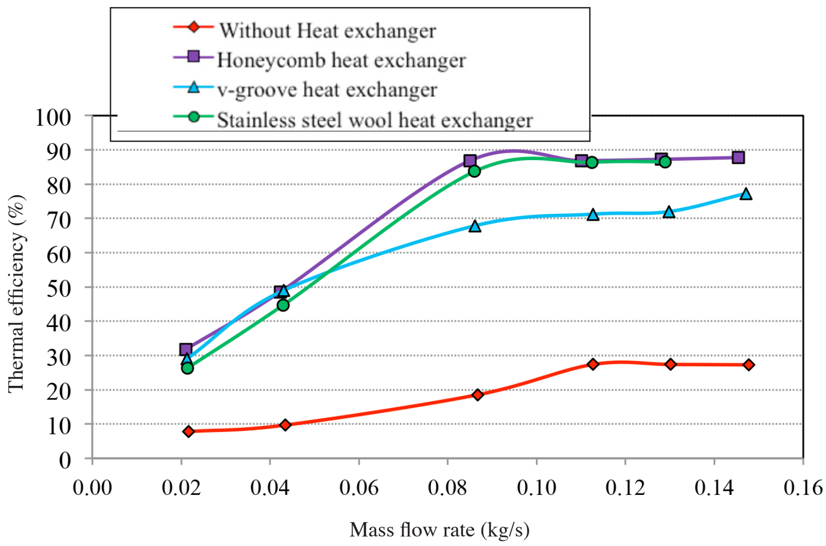

FIGURE 9. Thermal efficiency, for all collectors

CONCLUSION

The aim of this experiment was to develop an efficient PV/T solar collector. Three different designs of heat exchanger namely V-groove, honeycomb and stainless steel wool, located at the back of the PV module has been tested individually. At irradiance of 828 W/m^2 and mass flow rate of 0.11 kg/s, the maximum thermal efficiency of the system with V-groove is 71%, stainless steel wool, 86% and honeycomb is 87%. The electrical efficiency of the system is 7.04%, 6.88% and 7.13%, respectively. It can be concluded from the results that the performance of a PV/T solar collector with hexagonal honeycomb heat exchanger is the most efficient. The structure of the honeycomb with large surface area touching to the back of the PV module and ability to make air flows uniformly enhance the heat transfer from the back of the PV module to the flowing air.

The findings from this experiment can be further investigated to be applied in solar drying system and space heating. It is simple for manufacturing process and compact as it can be easily implemented for building integration.

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