Parametric studies of an active solar water heating system with various types of PVT collectors

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Abstract. This study simulated active photovoltaic thermal solar collectors (PV/T) for hot water production using TRNSYS. The PV/T collectors consist of the amorphous, monocrystalline and polycrystalline. The long-term performances for the glazed and unglazed PV/T collectors were also evaluated. In this simulation, the design parameters used were collector area of 4 m², collector slope angle of 15 degree and mass flow rate to the collector area ratio of 8–20 kg/hm². In addition the tank height between 0.9 m to 1.1 m for unglazed PV/T collectors and 0.9 m to 1 m for glazed collectors, as well as the storage tank volume between 200 and 300 L has been used. The climate parameters used were solar radiation levels range of 4–4.9 kWh/m², the mean ambient temperature in the range of 25–28°C. The results of the simulation indicated that there was an increase in solar fraction and electrical power output of the active PV/T hot water system.

Keywords. PV/T collectors; TRNSYS simulation; solar water heater; solar fraction; packing factor; glazed and unglazed collector.

1. Introduction

Increased utilisation of renewable energy resources is strategically important in the long term as it will contribute to the sustainability of energy supply. It also will help to address the environmental concerns that emerge due to the emission of gases and particulates as a result of energy generated from fossil fuels (Hitam 1999). Solar radiation in Malaysia, which is entirely equatorial, has an annual average daily solar irradiation of 4.5 kWh/m² and an annual average daily sunshine duration of about 4–5 h. Therefore, the climatic conditions of Malaysia are favourable for the development of solar energy technology (Daghigh *et al* 2011; Othman *et al* 1993).

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Figure 1. Typical hot water consumption pattern.

Direct solar energy technology can be divided into two namely (a) solar thermal systems and (b) solar photovoltaic (PV) systems. Normally, the two systems are used separately to generate hot air or hot water and electricity respectively. A photovoltaic thermal collector or PV/T generates both electricity and thermal energy simultaneously. The PV/T collectors are used since the overall photovoltaic thermal efficiency will increase and also will save valuable space.

Solar thermal opportunities do exist for the industrial process heat industries that require the processing of hot water or pre-heating of water ahead of other forms of thermal input. There were 10,000 domestic solar water heaters installed in Malaysia in 2002 (most of them were of the thermosyphon type) with an annual growth rate of 10–15%. In addition, the heaters installed were both locally manufactured and imported, with the majority of imports from Australia. Notably, the solar PV applications in Malaysia are limited to mainly standalone PV systems, especially for rural electrification and net metering applications where the systems receive a significant subsidy (Renewable Energy in Asia 2005).

Many researchers have acknowledged the performance of solar water heating systems using the PV/T collectors, which has resulted in the rapid growth of both theoretical and applied research studies on the thermosyphon and active water heater systems. Among the computer simulation programmes and tools (i.e. from simple domestic hot water systems to the design and simulation of building their equipment, as well as control strategies, occupant behaviour, alternative energy systems, etc.), TRNSYS has been developed for the transient simulation of systems (Klein 1996). It is an ideal programme that has its original applications to perform the dynamic simulation of the behaviour of a solar hot water system for a typical meteorological year.

Some of the relevant studies regarding the modelling of PV/T water heaters using TRNSYS to predict the performance of the systems are presented in table 1. In terms of hot water consumption pattern, most families in Malaysia use hot water in the evening and at night. A survey among 52 families located in Seri Petaling, Kuala Lumpur, in March 2004, indicated that most of the families used hot water just for shower (i.e. 56 cases) after 6 pm and just once a day. Others (six cases) used it twice a day, i.e. once in the evening and once in the early morning. The finding also revealed that the average number of family members in the urban areas in Malaysia was five persons. For each person, the usage of 25–30 L of hot water was considered adequate. It means that, 150 L of water per day per family should be enough for hot water consumption in Malaysia (Zahedi *et al* 2007). The typical hot water consumption pattern established by Mutch (1974) and Duffie & Beckman (1991) was employed for this work as it coincides with the Malaysian requirements as shown in figure 1.

The electricity consumption per household depends very much on the family size, living habits, number and age of electrical appliances and their hour of use. A study in 1998 estimated that an

average family in a low cost house spent about RM65 (approximately US\$17) per month, while the electricity in the medium cost house was approximately RM110 (US\$30) per month. Furthermore, the average daily consumption of electricity per household of five people was assumed to be approximately 15 kWh. This was equivalent to the typical daily average of electricity consumption of RM95 per month for a medium cost house (Faridah 2003). The basic electricity tariff for residential sector in Malaysia was RM0.22 per kWh.

This research work aimed to model, simulate and predict the long-term performance of a photovoltaic/thermal hot water system under the meteorological conditions of Malaysia. The type of photovoltaic panels used was amorphous silicon thin film, monocrystalline silicon and polycrystalline silicon solar cells.

Table 1. Some studies on PV/T water heating systems using TRNSYS.

Author and year	Type of system	Type of cells	Remarks
Rockendorf <i>et al</i> (1999)	–	–	Simulation modules were developed and implemented in TRNSYS 14.1 (1994) in order to simulate the thermoelectric collector and the photovoltaic-hybrid collector behaviour in the typical domestic hot water systems. The discussion of the results showed that the electric output of the PV-hybrid collector was significantly higher than that of the thermoelectric collector.
Kalogirou (2001)	Active system	Monocrystalline-silicon	The results of the simulation showed that the optimum water flow rate of the system was 25 l/h. The hybrid system increased the mean annual efficiency of the PV solar system from 2.8% to 7.7%. In addition, it covered 49% of the hot water need of a house, and thus, increased the mean annual efficiency of the system to 31.7%. The life cycle savings of the system were Cy£790.00, while the payback time was 4.6 years.
Chow <i>et al</i> (2005)	–	Amorphous silicon	The a-Si PVT collector arrays covered two-third of the west- and south-facing external facades. The system was able to support one-third of the thermal energy required for water heating of multi-storey apartment buildings in Hong Kong.
Kalogirou & Tripanagnostopoulos (2006)	Thermosyphonic and active system	Polycrystalline and amorphous silicon	The results showed that while the electricity generations were higher for pc-Si cells, the thermal contributions were slightly higher for a-Si cells. The a-Si modules also had better cost/benefit ratios owing to their lower initial costs.

Table 1. (contd)

Author and year	Type of system	Type of cells	Remarks
Fraisse <i>et al</i> (2007)	Active system	Monocrystalline and polycrystalline	For a system that included a glass-covered collector and localised in Maçon area in France, it was shown that the annual photovoltaic cell efficiency was 6.8%, which presented a decrease of 28% in comparison with a conventional non-integrated PV module that gave the percentage of 9.4% of the annual efficiency. This was obviously due to the temperature increase related to the cover. On the other hand, it was shown that without a glass cover, the efficiency was 10%, which was 6% better than the standard model due to the cooling effect.

2. The system configuration

The photovoltaic thermal water heater system configuration was simulated using TRNSYS (TRaNsient SYstem Simulation) as shown in figure 2. This system consists of a PV/T collector, storage tank, auxiliary heater, the load, pump and ON/OFF Controller. Solar energy is collected using the PV/T collector's absorber plate and the cold water is heated utilising the solar energy usage in the PV/T collector. A pump is employed to circulate water between the collector and the storage tank. Auxiliary heating is done in the storage tank if the hot water temperature is lower than the set point temperature. The auxiliary heat source is located at the upper third of the tank, keeping the lower third as cool as possible. This will cause the solar system to operate at a higher efficiency because the relatively low-temperature water is delivered to the collectors from the bottom of the tank. The system also considers a diverter valve for use on the hot water heat distribution system in order to enter cold water to the storage tank, and mix the cold water with hot water before reaching the load.

An ON/OFF Differential Controller which turns the pump on when the water in the collector is about 10°C warmer than the water in the tank, and it turns the pump off when the temperature difference approaches 0°C in this system. A time dependent forcing function which has a behaviour characterized by the hot water consumption profile pattern shown in figure 1 has been considered in this simulation. The cycle will repeat every 24 h.

2.1 Analysis of PV/T

In this study, the annual solar thermal fraction and the electrical power output were used as the indicators for determining the system performance. The annual solar fraction of the system is defined as follows (Buckles & Klein 1980):

$$f = Q_{Load} - Q_{Aux} / Q_{Load} \quad (1)$$

Figure 2. A schematic diagram of the active PV/T hot water system.

Q_{Load} is the energy delivered to the load and Q_{Aux} is the energy supplied by the auxiliary heater. The collector's characteristic factors may not be a good indicator for calculating the performance of the solar water heaters, since the collector is only one component of the whole system. Using the solar fraction of the system as an indicator is better than the collector's characteristic factors since it measures the performance of the whole system for the specified operation strategy (Shariah *et al* 1999).

A general equation for the solar thermal collector efficiency can be obtained from the Hottel–Whillier equation is as follows:

$$Q_u = A_C F_R [(\tau\alpha)_n \cdot G_T - U_L (T_i - T_a)]. \quad (2)$$

To eliminate the need to determine the plate temperature, a collector heat removal factor (F_R) has been introduced (Duffie & Beckman 1991; Hottel & Willier 1958):

$$F_R = \frac{m \cdot C_P}{A_C \cdot U_L} \cdot \left[1 - e^{-\frac{A_C \cdot U_L \cdot F'}{m \cdot C_P}} \right], \quad (3)$$

where the collector efficiency factor is defined as

$$F' = \frac{1/U_L}{w \left[\frac{1}{U_L \cdot (D_h + (w - D_h) \cdot F)} + \frac{1}{w \cdot h_{ca}} + \frac{1}{2 \cdot (D_h + b)} \right]}. \quad (4)$$

The fin efficiency factor F is given by

$$F = \frac{\tanh \left[m \cdot \frac{w - D_h}{2} \right]}{\frac{w - D_h}{2}} \quad (5)$$

$$m = \sqrt{\frac{U_L}{k_{abs} \cdot L_{abs} + K_{pv} \cdot L_{PV}}}. \quad (6)$$

The collector's overall loss coefficient U_L is the sum of the top, bottom and edge loss coefficients:

$$U_L = U_t + U_b + U_e. \quad (7)$$

The back loss coefficient is calculated by using the following equation:

$$U_b = \frac{K_b}{L_b}. \quad (8)$$

The edge loss coefficient based on the collector area is as follows:

$$U_e = \frac{(UA)_{edge}}{A_C}. \quad (9)$$

The top loss coefficient is

$$U_t = \frac{1/N}{\frac{c}{T_{pm} \left(\frac{T_{pm} - T_a}{N + f} \right)^e + 1/h_w}} + \frac{\sigma (T_{pm} + T_a) \cdot (T_{pm}^2 + T_a^2)}{\frac{1}{\varepsilon_p + 0.00591 \cdot N \cdot h_w} + \frac{2 \cdot N + f - 1 + 0.133 \cdot \varepsilon_p}{\varepsilon_g} - N}. \quad (10)$$

The useful energy gain by the collector heats the collector's fluid, is

$$Q_u = m \cdot C_p (T_o - T_i). \quad (11)$$

Thus, the useful energy gain can be rewritten as follows:

$$Q_U = F_R A_C [(\tau\alpha)_n \cdot G_T - U_L (T_i - T_a)] = m \cdot C_p (T_o - T_i). \quad (12)$$

The electrical power output (E) depends on the instantaneous operating temperature T_c of the PV module. It can be expressed as a function of the packing factor P of the PV module, the effective transmissivity s_g of the glazing and the electrical conversion efficiency g_e at the reference temperature 25°C as well as the temperature coefficient φ_c of the solar cell (Chow *et al* 2006):

$$E = GP\tau_g\eta_e [1 - \varphi_c (T_c - T_{25})]. \quad (13)$$

2.2 Exergy gain

Overall exergy gain of the PV/T water collector can be expressed as (Petela 2003; Mishra & Tiwari 2013):

$$\sum Ex_{in}(Ex_{th} + Ex_{pv}) = \sum Ex_d \quad (14)$$

$$Ex_{in} = A_C N_C I(t) \left[1 - \frac{4}{3} (T_a/T_S) + \frac{1}{3} (T_a/T_S)^4 \right]. \quad (15)$$

$$\text{Overall exergy of PVT} = Ex_{th} + Ex_{pv} \quad (16)$$

$$\text{Overall exergy} = Q_u \left(1 - \frac{T_a + 273}{T_{fo} + 273} \right) + \eta_C A_C N_C I(t) \left[1 - \frac{4}{3} (T_a/T_S) + \frac{1}{3} (T_a/T_S)^4 \right] \quad (17)$$

η_C is a solar cell temperature dependent electrical efficiency (Daghighi *et al* 2011):

$$\eta_C = \eta_r(1 - \beta(T_C - T_r)). \quad (18)$$

T_C is the average temperature of cells, T_r is the reference temperature, η_r is reference efficiency of the module.

The exergy efficiency of PVT water-heating system is defined as follows (Tiwari *et al* 2009):

$$\eta_{ex} = 1 - \frac{E_{Xd}}{E_{in}}. \quad (19)$$

3. Results and observations

The annual system performance has been relatively insensitive to storage capacity as long as the capacity was more than 50 L of water per square metre of the collector. Moreover, when the costs of storage were considered, the annual performance was sensitive over a wide range of 50–200 L of water per square metre of the collector. The storage tank considered for this simulations is based on the f-chart, which was developed for a storage capacity of 75 L of the stored water per square metre of the collector area (Duffie & Beckman 1991; Klein *et al* 1977). The collector mass flow rate to the collector area ratio was also initially set equal to 40 kg/hm², which was within the recommended range in the literature (Baughn & Young 1984; Hobbi & Siddiqui 2009).

The weather data for Kuala Lumpur, Malaysia was considered for the simulation of this system. Variations of dry ambient temperature, solar radiation and wind velocity in the interim one year for each month are shown in figure 3. Notably, the average daytime temperature in Kuala Lumpur ranges from 25.7°C to 27.2°C in a monthly round, the monthly average daily total radiation on the tilted surface is between 4 kWh/m² and 4.9 kWh/m² and the monthly mean of wind speed ranges from 2.1 m/s to 3.6 m/s. In order to harness the energy from the sun, the amount of average monthly total radiation on the tilted surface was taken into a good account. The effect of ambient temperature and solar radiation on the thermal and electrical performances of the PV/T collectors was studied. However, further studies are needed in order to investigate the influence of wind speed on the performance of this solar technology.

Figure 3. Monthly variations of ambient temperature, solar radiation and wind speed.

3.1 Effects of collector area on the performance of PV/T water heater

The selection of the optimum collector area for a given system has always been ultimately an economic decision. Moreover, the cost of an additional collector area and a system capacity must be weighed against the diminishing return in the solar fraction gained. The index used to represent the contribution of the solar thermal system is the solar fraction, which is the fraction of the total energy required by the load that is supplied by the solar system (Hitam 1999). The dependence of the solar fraction of photovoltaic thermal collectors with and without a glass cover is depicted in figures 4a and 4b for different collector areas over a period of one year.

Seemingly, as can be clearly seen in figures 4a and 4b, the solar fraction was high for the glazed cover collectors, whereas it was low for the unglazed ones. The solar fraction was almost near unity for the glass-covered collectors with the collector area higher than 5 m^2 since the hot water produced by the solar energy and the temperature of it is always in demand. In comparison with the glazed cover collectors, the solar fractions of the unglazed collectors never reached near 1. For the collector area of 1 m^2 , the average yearly solar fractions for the unglazed and glazed cover collectors were 38.3%, 37.4% and 37.2% for amorphous, polycrystalline and monocrystalline silicon unglazed PV/T collectors, respectively. On the other hand, as for amorphous, polycrystalline and monocrystalline silicon glazed PV/T collectors, the findings were 46%, 44.5% and 44%, respectively. Furthermore, it appeared that the average solar fraction for the glazed collectors was more than the unglazed collectors. This finding can be attributed to the fact that the average yearly solar heat gains with the collector area of 1 m^2 were 855.3 kW, 836.8 kW and 831 kW for amorphous, polycrystalline and monocrystalline silicon unglazed collectors, respectively; whereas for the glazed collectors, the results were 1,017.9 kW, 985.8 kW and 975.2, correspondingly. As the collector area exceeded 1 m^2 , the solar fraction of the collector with and without a glass cover was increased. In addition, in the collector area of 4 m^2 , the results reached 65.2%, 63.6% and 63% for the coverless PV/T collectors, while 96.4%, 95.7% and 95.3% for the glazed PV/T collectors, respectively. For the glazed system, the solar fraction tended to increase up to 95% with the collector area of greater than 4 m^2 , whereas the maximum values of the unglazed collectors reached 80%, 77% and 76% for the collector area of 60 m^2 .

Figure 4. Variations of annual solar fraction versus the collector area for PV/T collectors. (a) Unglazed and (b) Glazed.

Figure 5. Yearly variations of electrical power output for the collector area of 1–80 m². (a) Unglazed and (b) Glazed.

Figures 5a and 5b show the comparisons between the average yearly electrical power output of the coverless and glazed covered PV/T collectors at different collector areas. It can be seen that the yearly mean electrical power output can be as low as 33.4 kW and 32.2 kW for amorphous unglazed and glazed PV/T collectors, and as high as 4,954.2 kW and 3,943.5 kW for monocrystalline unglazed and glazed PV/T collectors, respectively. Moreover, it can be observed that the value of electrical power output at each collector area for the coverless collectors was higher than that of the glazed collectors. The glazing contributed much towards increasing optical losses of the collectors. Conversely, on the thermal point of view, the coverless collectors provided more heat gain. Regarding the collector area, it was found that the electrical power output enhanced with the collector area. As seen in figures 7a and 7b, there was an increasing movement for the electrical power output with the collector area from 1 m² to 10 m². Nevertheless, the differential trend for coverless and uncovered collectors was very small. The difference in the electrical power output was significantly more noticeable for the collector area greater than 10 m².

3.2 Influence of collector slope angle on the performance of PV/T water heater

A solar collector needs to be tilted at the correct angle to maximize the performance of the system. Solar fraction by the PV/T collectors in Malaysia for glazed and unglazed PV/T collectors is illustrated in figures 6a and 6b. Simulation results indicated that the optimum collector slope for amorphous, monocrystalline and polycrystalline silicon solar cells varied from latitude 0 degree to latitude 5 degree, depending on the heat gain and solar fraction by the solar system and can be seen in figure 6. In practice, due to natural degradation processes that occur on the solar collectors mounted outdoors and with respect to dropping photovoltaic (PV) cell performance due to dust deposition on the cells (Goossens & van Kerschaever 1999), the 15° collector slope angle has been considered for metrological conditions of Malaysia. In addition, at this angle, the rain in the afternoon will act as a natural cleansing mechanism for the solar collectors.

Figures 7a and 7b show the comparison between the average yearly electrical power output of the glazed and unglazed PV/T collectors. It can be clearly seen that the amount of power output dropped with the collector slope growth. This effect was more dominant as the slope angle increased. The peak values were 132.5, 292 and 345.3 kW for the coverless amorphous, polycrystalline and monocrystalline silicon solar cells, whereas 119, 263.3 and 311.8 kW for amorphous, polycrystalline and monocrystalline silicon solar cells. The glazed cover collectors

Figure 6. Variation of solar fraction versus the collector slope. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

Figure 7. Variation of electrical power output versus the collector slope. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

can be found at the inclined angle of 0° , respectively. Maximum annual electrical power output, solar fraction and heat gain occurred in the tilt angle between 0 and 5 degree in the hot and humid climates of Malaysia. It was concluded that the slope of PV/T collectors considered 15 degree in use due to technical issue and reduction of electric power output because of dust accumulation, especially in the glazed collectors.

3.3 Mass flow rate and system performance

The effects of mass flow rate of the pump on the system performance were plotted and shown in figures 8a and 8b for the uncovered and covered cases, respectively. From the figures, it can be seen that, as the mass flow rate increased from 4 kg/h to 80 kg/h, the solar fraction of the

Figure 8. Variation of annual solar fraction versus mass the flow rate for unglazed PV/T collectors. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

Figure 9. Average electrical power output versus the mass flow rate for the unglazed PV/T collectors. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

system improved for the coverless and glazed PV/T collectors. Since the amount of mass flow rate increased further, the solar fraction decreased as well.

Figures 9a and 9b show the variation of electrical power output versus the mass flow rate. As it is known, one of the main advantages of crystalline silicon over amorphous silicon is that, it has better electrical properties, as clearly shown in the figures. Also, it can be seen that the electrical properties of the monocrystalline solar cells had an upward trend in contrast to the polycrystalline solar cells.

The results indicated that as long as the mass flow rate was about 4–80 kg/h, the electrical power output rose for both glazed and unglazed collectors. The highest electric power outputs

were found to be 130.3, 287.2 and 339.6 kW for the coverless collectors, and 116, 257 and 305 kW for the glazed collectors, respectively. Subsequently, the electrical output started to stay constant. The optimum values were found to be in the mass flow rate between 16 and 80 kg/h.

3.4 Impact of storage tank geometry

3.4a Effects of the storage tank height: The average yearly performance of the system based on the height of the storage tank is shown in figures 10a and 10b. As can be observed from these figures, the annual solar fraction for the unglazed amorphous, polycrystalline and monocrystalline solar cells augmented with the increasing height of the storage tank from 0.3 m to 1.2 m, and decreased with a further increase in the height. Furthermore, figures 8a and 8b show the maximum ranges of solar fraction for the height of around 0.9–1.2 m for the coverless collectors; i.e. amorphous: 0.66–0.67, polycrystalline: 0.64–0.65, and monocrystalline: 0.64–0.645. Furthermore, for the height of 0.6–1 m for the covered solar collectors, the maximum ranges of solar fraction were as follows; amorphous: 0.973–0.975, polycrystalline: 0.968–0.969, and monocrystalline: 0.964–0.965. Therefore, a reduction in the solar fraction should be expected for the height of greater than 1.1 and 1 m for the coverless and covered collectors, respectively.

The influence of the increasing height of storage tank on the electrical power output for the glazed and unglazed PV/T collectors are shown in figures 11a and 11b. As observed from these figures, with the rising height of the storage tank from 0.3 m³ to 2.1 m³, the average power output stayed constant at around 130.1, 286.8 and 339.2 kW for the unglazed amorphous, polycrystalline and monocrystalline cells, correspondingly; and 115.9, 256.7 and 304.1 kW for the glazed amorphous, polycrystalline and monocrystalline cells, respectively.

3.4b Effects of the storage tank volume: The solar fraction of the system with the collector area of 4 m² required the water temperature of 60°C. Figures 12a and 12b show the variable storage tank volume for the unglazed and glazed PV/T collectors. Seemingly, for the unglazed system, as the storage tank volume increased from 0.1 to 0.3 m³, the solar fraction rose from

Figure 10. Variations of solar fraction versus the height of storage tank. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

Figure 11. Variations of electrical power output versus the height of the storage tank. (a) No. of glass covers = 0. (b) No. of glass covers = 1.

Figure 12. Variations of solar fraction versus the tank volume. (a) No. of glass covers = 0, (b) No. of glass covers = 1.

about 0.68 to 0.73, 0.67 to 0.715 and 0.667 to 0.71 for amorphous cells, polycrystalline one and monocrystalline cells, accordingly. A further increase in the storage tank volume (0.3–0.4 m^3) resulted in the decreasing solar fraction, i.e. 0.73 to 0.72, 0.716 to 0.71 and 0.71 to 0.70 for amorphous cells, polycrystalline one and monocrystalline cells, respectively. The effects of the storage volume on the solar fraction for the glazed PV/T collectors (figure 12b) revealed that the solar fraction with the tank volume from 0.1 to 0.2 m^3 possessed a sharp upward trend; i.e. 0.974–0.994, 0.971–0.992 and 0.97–0.99 for the glazed amorphous cells, polycrystalline one and monocrystalline cells, respectively. In addition, as long as the tank volume rose more (i.e. from 0.2 to 0.4 m^3), the solar fraction increased very slowly; i.e. 0.994–0.997, 0.992–0.997 and 0.99–0.996 for amorphous cells, polycrystalline one and monocrystalline cells, correspondingly.

As expected and as can be seen from figures 13a and 13b, there was no enormous effect on the electrical power out of the PV/T collectors, as long as the tank volume increased. From the results of the simulation for the unglazed case, it can be depicted that the electrical power output increased from 129.1 to 130.3 kW, 284.7 to 287.1 kW and 290.5 to 305.8 kW for amorphous

Figure 13. Variations of electrical power output versus the tank volume. (a) No. of glass covers = 0, (b) No. of glass covers = 1.

Figure 14. Variations of solar fraction versus the set point temperature. (a) No. of glass covers = 0, (b) No. of glass covers = 1.

cells, polycrystalline one and monocrystalline cells, respectively. The results also showed that the electrical power output of the glazed collectors improved slightly by the tank volume; i.e. 110.4–116.4 kW, 245.2–258.1 kW and 290.5–305.8 kW, respectively.

3.4c Impact of the set point temperature: The influence of set point temperature on the solar fraction is shown in figures 14a and 14b. The storage tank of the PV/T water heater system was equipped with a specified heating element that was activated in response to the thermostatic control switches and it would start whenever the water in the water heater tank was below the set point temperature. Seemingly, a real difference of solar fraction can be seen when the set point temperature changed, particularly for the unglazed PV/T collectors. A higher set point temperature resulted in a poor thermal stratification, or warmer water entering the collector from the tank, resulting in lower collector efficiency and lower solar fraction. As can be seen in figures 15a and 15b, a small change in the electrical power output was observed when the set point temperature was altered.

Figure 15. Variations of solar fraction versus the set point temperature. (a) No. of glass covers = 0, (b) No. of glass covers = 1.

Figure 16. Variations of solar fraction versus the packing factor. (a) No. of glass covers = 0, (b) No. of glass covers = 1.

3.5 Packing factor

The variations of PV/T water heater performance with the packing factor (the fraction of absorber plate area covered by the solar cells) for both glazed and unglazed PV/T cells are shown in figures 16a and 16b. The figures show the average yearly solar fraction for various packing factors. For both glazed and unglazed conditions, the increment of packing factor resulted in the decreasing solar fraction. It appeared that this effect for the coverless PV/T collectors was sharper than the glazed ones. It can be seen that the solar fraction went down very little even as the packing factor increased from 0.1 to 1. In addition, a slow decrease of the fraction from 0.72 to 0.69, 0.715 to 0.67 and 0.714 to 0.66 can be reached for the uncovered amorphous, polycrystalline and monocrystalline solar cells, respectively. On the contrary, for the glazed PV/T collectors, the declining trend was the same for different solar cells, but it dropped slightly from 0.998 to 0.996, 0.997 to 0.993 and 0.996 to 0.991, subsequently. This can be attributed mainly

Figure 17. Variations of electrical power output versus the packing factor. (a) Unglazed, and (b) Glazed.

Figure 18. Average yearly variations of exergy efficiency for unglazed PVT collector.

to the fact that, regardless of the values of the packing factor, the solar fraction of the covered PV/T collectors was higher than the collectors with the glass covers, thus, increasing the packing factor and reducing the amount of solar fraction of the glazed collectors more. Keeping this in mind, in this study by considering the two different cases, namely glazed and unglazed PV/T cells, collectors partially covered by PV modules.

The electricity produced by the photovoltaic thermal collector for a-Si, Pc-Si and Mc-Si cells based on the variations of packing factors in both glazed and unglazed configurations is presented in figures 17a and 17b. It can be seen from the figures that the electrical energy produced by the monocrystalline for the glazed and unglazed collectors was more than that of the polycrystalline and amorphous cells in different packing factors. Electricity production increased by the increment in the packing factor for both coverless and covered configurations. It was noteworthy that the average percentage of the electrical power outputs for the coverless mono c-Si, Poly c-Si and amorphous cells were 12.7%, 13.0% and 13.9% more than that of the covered ones, as the packing factor increased from 0.1 to 1, respectively.

Figure 19. Average yearly variations of exergy efficiency for glazed PVT collector.

Figures 18 and 19 show the average yearly variations of exergy efficiencies of unglazed and glazed PVT collectors. It is found that maximum exergy efficiency can be seen for polycrystalline silicon-based collector whereas minimum PVT exergy efficiency is seen for amorphous silicon PVT collector.

4. Conclusions

In Malaysia, there is huge potential for solar water heating in the residential and domestic sectors. For the residential sector, approximately 2,500,000 households are suitable for integration with solar thermal heaters. Hence, the use of solar water heater shall improve public awareness in energy conservation in the hot water production of their buildings, and subsequently increase the market of the solar energy systems as well as reduce greenhouse gas emission and the amount of LPG used. In addition, potential applications exist in solar hot water for hotels, hospitals, texture factories and the food industries.

One of the ingenious methods of solar energy conversion systems is the photovoltaic thermal solar collector, which is very attractive for solar applications, in which limited space and area related to installation cost are of primary concern. Therefore, the combination of the PV/T collector and the water heater system for domestic and residential applications for producing hot water and electricity is feasible. Needless to say, there is no study and information regarding PV/T water heaters in Malaysia. This is due to the fact that modelling and theoretical studies of the active glazed and unglazed photovoltaic thermal solar water heaters using TRNSYS under the meteorological conditions of hot and humid climates of Malaysia based on the weather data of Kuala Lumpur have not yet been conducted. It should be noted, that the amorphous silicon, polycrystalline silicon and monocrystalline silicon of PV modules were studied in this research. The following are the conclusions from the results of the simulations, which were conducted in order to evaluate the optimum system parameters.

4.1 The optimum collector area for PV/T water heater

In order to design a cost-effective solar hot water system with a satisfactory performance, a collector area plays an important role. Therefore, the selection of an optimum collector area is

important to achieve the adequate performance. The results of this simulation study indicated that the solar fraction was almost near unity for the glass-covered collectors with the collector area higher than 5 m^2 , since the hot water produced by the solar energy and the temperature is always be in demand.

In comparison with the glazed cover collectors, the solar fractions of the glazed collectors never reached near one. The solar fractions for 4 m^2 of the unglazed collector area were 65.2%, 63.6% and 63%, and as for the collector area of 5 m^2 , it was able to provide 68.3%, 66.8% and 66.1% of hot water (60°C) for amorphous, polycrystalline and monocrystalline silicon cells, respectively. In addition, the solar fraction increased from 70.7% to 79.3%, 68.9% to 77% and 68.3% to 76.1% as the collector area rose from 6 m^2 to 20 m^2 for amorphous, polycrystalline and monocrystalline silicon cells, accordingly. Furthermore, the solar fractions for 4 m^2 of the glazed collector area were 96.4%, 95.7% and 95.4% for amorphous, polycrystalline and monocrystalline silicon cells, respectively. It can be concluded that using 4 m^2 of the collector area can be considered as the suitable size for the glazed (95.4%–96.4%) and unglazed PV/T hot water system (63%–65.2%), and thus, can contribute to the cost-effectiveness of the system. For both glazed and unglazed condition, the increase of collector area would lead to an increase in electrical power output.

4.2 *The most favourable collector slope angle for collector*

Solar collectors need to be tilted at the correct angle to maximize the performance of the system. In this study, the optimum collector slope for amorphous, monocrystalline and polycrystalline silicon solar cells varied from latitude 0 degree to latitude 5 degree, depending on the solar fraction and maximum annual electrical power output by the solar system. In practice, due to natural degradation processes that occur on solar collectors mounted outdoors and with respect to dropping photovoltaic (PV) cell performance due to dust deposition on the cells, it can be concluded that the slope of PV/T collector considers 15 degree in use due to technical issue and reduction of electric power output because of dust accumulation especially in glazed collectors.

4.3 *The ideal pump flow rate*

The effect of mass flow rate indicated that the higher flow rate before a certain point (80 kg/h or 20 kg/hm^2) had led to the rapid improvement of the solar fraction and electrical power output for the uncovered and covered PV/T collectors. However, a further increase in the mass flow rate from 80 kg/h to 160 kg/h slowly decreased the amount of solar fraction and useful heat gain. The maximum values of solar fraction for mass flow rate to the collector area ratio of 20 kg/hm^2 were 73%, 71.6% and 71% for amorphous, polycrystalline and monocrystalline silicon cells, respectively. In comparison with the unglazed PV/T collectors, these values were found to be 99.7%, 99.6% and 99.5% for amorphous, polycrystalline and monocrystalline silicon cells, respectively for the glazed PV/T collectors. Therefore, the mass flow rates to the collector area ratio of $8\text{--}20 \text{ kg/hm}^2$ or $32\text{--}80 \text{ kg/h}$ were the ideal pump flow rates for this system.

4.4 *The ideal storage tank geometry*

4.4a *Effects of the storage tank height:* The effects of the storage tank height on the solar fraction were apparently significant. When the height of the storage tank increased from 0.3 m to 1 m , the annual solar fraction for the glazed and unglazed amorphous, polycrystalline and monocrystalline solar cells augmented and decreased with a further decrease in the height. Hence, the optimum storage tank heights were around $0.9\text{--}1.1 \text{ m}$ for the unglazed PV/T collectors and $0.9\text{--}1 \text{ m}$ for the glazed collectors.

4.4b Effects of the storage tank volume: For the unglazed system, as the storage tank volume increased from 0.1 to 0.3 m³, the solar fraction rose from about 0.68 to 0.73, 0.67 to 0.715 and 0.667 to 0.71 for amorphous cells, polycrystalline one and monocrystalline cells, respectively. Further increasing the storage tank volume (0.3–0.4 m³) had led to the decreasing solar fractions, i.e. 0.73–0.72, 0.716–0.71 and 0.71–0.70 for amorphous cells, polycrystalline one and monocrystalline cells. The effects of storage tank volume on the solar fraction for the glazed PV/T collectors, as shown in figure 12b, revealed that the solar fraction with the tank volume from 0.1 to 0.2 m³ possessed a sharp upward trend, i.e. 0.974–0.994, 0.971–0.992 and 0.97–0.99 for amorphous cells, polycrystalline one and monocrystalline cells, respectively. In addition, as long as the tank volume rose more, i.e. from 0.2 to 0.4 m³, the solar fraction increased very slowly, i.e. 0.994–0.997, 0.992–0.997 and 0.99–0.996 for amorphous cells, polycrystalline one and monocrystalline cells, correspondingly. Hence, the optimum volume of storage tank was between 200 and 300 L.

4.4c Impact of the set point temperature: Set point temperature has a great influence on the performance of a system. Evidently, the performance of the PV/T water heater system was affected by the changing set point temperature. It appeared that there was no difference between the solar fraction of the glazed and unglazed PV/T collectors when the set point temperature was 35°C and the value was 1. As the set point temperature increased for the unglazed collectors from 40°C to 60°C, the solar fraction decreased from 0.992 to 0.73 for amorphous silicon, 0.99 to 0.716 for polycrystalline and 0.989 to 0.71 for monocrystalline. Moreover, the range of variations in the solar fraction was small for the unglazed collectors and differed from 1 to 0.995.

It should be concluded that storage tank geometry has no important effect on electrical power output.

4.5 Packing factor

For both glazed and unglazed conditions, the increment of the packing factor resulted in the decreasing solar fraction, whereas this effect for the coverless PV/T collectors was found sharper than the glazed ones. For amorphous, polycrystalline and monocrystalline silicon cells, the maximum solar fraction was found in the amorphous cells, while the minimum one was obtained from the monocrystalline solar cells. Apparently, the curves followed the same pattern for the unglazed PV/T collectors. However, electrical power output increases significantly with increase of packing factor.

4.6 Exergy analysis

The exergy of a system is the maximum useful work possible. The average yearly exergy efficiency decreased for amorphous silicon PVT collector in comparison with poly and monocrystalline PVT collectors.

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