



PERFORMANCE EVALUATION OF SOLAR PHOTOVOLTAIC/THERMAL SYSTEMS

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Abstract—The major purpose of the present study is to understand the performance of an integrated photovoltaic and thermal solar system (IPVTS) as compared to a conventional solar water heater and to demonstrate the idea of an IPVTS design. A commercial polycrystalline PV module is used for making a PV/T collector. The PV/T collector is used to build an IPVTS. The test results show that the solar PV/T collector made from a corrugated polycarbonate panel can obtain a good thermal efficiency. The present study introduces the concept of primary-energy saving efficiency for the evaluation of a PV/T system. The primary-energy saving efficiency of the present IPVTS exceeds 0.60. This is higher than for a pure solar hot water heater or a pure PV system. The characteristic daily efficiency η_s^* reaches 0.38 which is about 76% of the value for a conventional solar hot water heater using glazed collectors ($\eta_s^* = 0.50$). The performance of a PV/T collector can be improved if the heat-collecting plate, the PV cells and the glass cover are directly packed together to form a glazed collector. The manufacturing cost of the PV/T collector and the system cost of the IPVTS can also be reduced. The present study shows that the idea of IPVTS is economically feasible too. © 2001 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The present commercial solar cell converts solar energy into electricity with a relatively low efficiency, less than 20%. More than 80% of the absorbed energy is dumped to the surroundings again after electric energy conversion. To raise the energy efficiency, many researchers attempted to develop hybrid PV and thermal (PV/T) collectors (Bergene and Bjerke, 1993; Bergene and Lovik, 1995; Fujisawa and Tani, 1997; Garg *et al.*, 1990; Hayakashi *et al.*, 1990; Lalovic, 1986/87).

The PV/T collector generates electric power and simultaneously produces hot water. The overall efficiency thus increases. Bergene and Lovik (1995) have shown theoretically that a total efficiency of 60–80% can be achieved with a PV/T collector. The recent test result (Fujisawa and Tani, 1997) shows that a thermal efficiency of about 60% can be obtained for a PV/T collector. However, all the aforementioned results for thermal efficiency were the instantaneous efficiency that is calculated or measured under the conditions of once-through flow at low and constant

inlet temperature. If the PV/T were combined with a water tank to make a PV/T system with water heating in a closed system, the inlet temperature will vary during a day and the thermal efficiency should be rated based on a daily test result. The daily thermal efficiency of a PV/T system is not yet very clear. One of the purposes of the present study is to show how much difference in thermal efficiency there is between a PV/T system and a conventional solar water heater.

Besides, we have noted that many conventional solar water heaters with natural circulation need parts assembled in situ. The concept of integrated design for water heating in a PV/T, i.e. integrated PV/T system (IPVTS), is thus proposed in the present study (Fig. 1). IPVTS can be entirely manufactured in a factory with good quality control and cost reduction due to mass production. An IPVTS will be installed directly at the application site with minimal mounting work and free of assembly. The only on-site work is the connection of the hot and cold water supply lines. Hence, IPVTS has the advantage of reducing the installation cost. IPVTS also can reduce the space needed for installation and the casing cost since the PV and the thermal units are integrated within a single casing.

For demonstration purposes, we designed an

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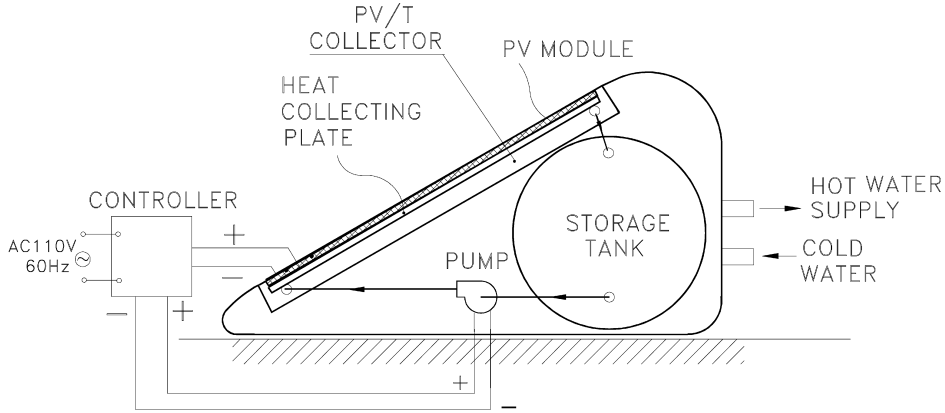


Fig. 1. Schematic diagram of integrated PV/T system (IPVTS).

IPVTS and measured the thermal performance using the daily-efficiency test procedure for a solar hot water heater (Huang and Du, 1991). The overall evaluation of an IPVTS is also carried out using the concept of primary-energy saving.

2. PV/T SYSTEM EVALUATION

Many researchers (Bergene and Bjerke, 1993; Bergene and Lovik, 1995; Fujisawa and Tani, 1997; Garg *et al.*, 1990; Hayakashi *et al.*, 1990; Lalovic, 1986/87) used the total efficiency η_o which is defined in Eq. (1), for evaluating the PV/T systems:

$$\eta_o = \eta_{th} + \eta_e. \quad (1)$$

It is known that the value of electric power and thermal energy differs due to the form of energy. Electric energy is a high-grade form of energy since it is converted from thermal energy. Hence, to correctly evaluate the energy saving of a PV/T system, we define the energy-saving efficiency, in terms of the primary-energy saving, as

$$E_f = \eta_e / \eta_{power} + \eta_{th} \quad (2)$$

where η_e is the electric power generation efficiency for solar PV; η_{power} is the electric power generation efficiency for a conventional power plant; η_{th} is the heat collection efficiency of the PV/T system. η_{power} is taken as 0.38 in the present study. For simplicity the efficiency of conventional heating systems has been assumed to be 100%. It has been found by Huang (1993) that the daily efficiency for most solar hot water heaters with a cold-water start (low initial water temperature daily) is around 0.50. This value will provide a criterion for checking the overall performance of a PV/T system. It is expected that the

primary-energy saving efficiency E_f for a PV/T system should exceed 0.50 in order to compete with a pure solar hot water system.

3. IPVTS HARDWARE DESIGN AND TESTS

The PV/T collector made in the present study comprises a commercial PV module and a heat-collecting plate (Fig. 2). A Solarex MSX60 polycrystalline solar PV module (467 mm × 1105 mm) (rated 60 Wp, 17.1 V peak voltage) was adopted to be combined with a heat-collecting plate. The heat-collecting plate adheres directly to the back of the commercial PV module. Thermal grease was used between the plate and the PV module for better contact. Below the heat collecting plate, a PU thermal insulation layer is attached using a fixing frame.

Two types of tube-in-sheet heat-collecting plates with $W/D=6.2$ and 10 have been made in the present study (Huang *et al.*, 1999). The first one ($W/D=6.2$) is made from extruded tube-in-sheet aluminum, the latter ($W/D=10$) uses copper tube which is attached to an aluminum plate using thermally conductive adhesive. However, the performance of the PV/T collectors with these two heat-collecting plates is not satisfactory. We thus designed a heat-collecting plate using a corrugated plate made of polycarbonate material. The flow channels in the heat-collecting plate are in the corrugated structure with $W/D=1.0$ (Fig. 3). The heat transfer can be greatly enhanced. The flow channel dimension is 6 mm in width, 4 mm in height, 0.6 mm in thickness, and 6 mm in rib spacing.

An IPVTS was first built using the PV/T collector combined with a water storage tank, which is insulated with 50-mm-thick PU foam. To enhance the heat transfer of the heat-collecting

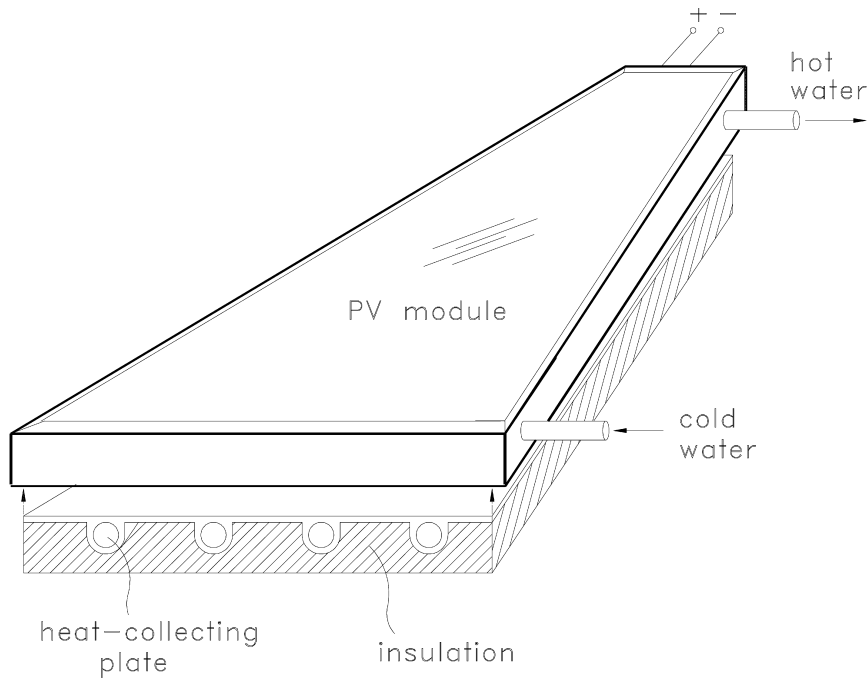


Fig. 2. Schematic diagram of PV/T collector.

plate, we installed a 3 W DC pump to circulate the water from the tank through the PV/T collector (Fig. 1).

For a solar water heater, there exists a critical inlet water temperature T_{in}^+ that is proportional to the ambient temperature T_a , the solar radiation

intensity I_T , and the thermal parameters of the solar collector (ratio of radiation heat absorption to convective heat loss) (Duffie and Beckmen, 1980). Once the water temperature in the storage tank $T_w (= T_{in})$ is higher than T_{in}^+ , the solar collector will have a negative efficiency for solar

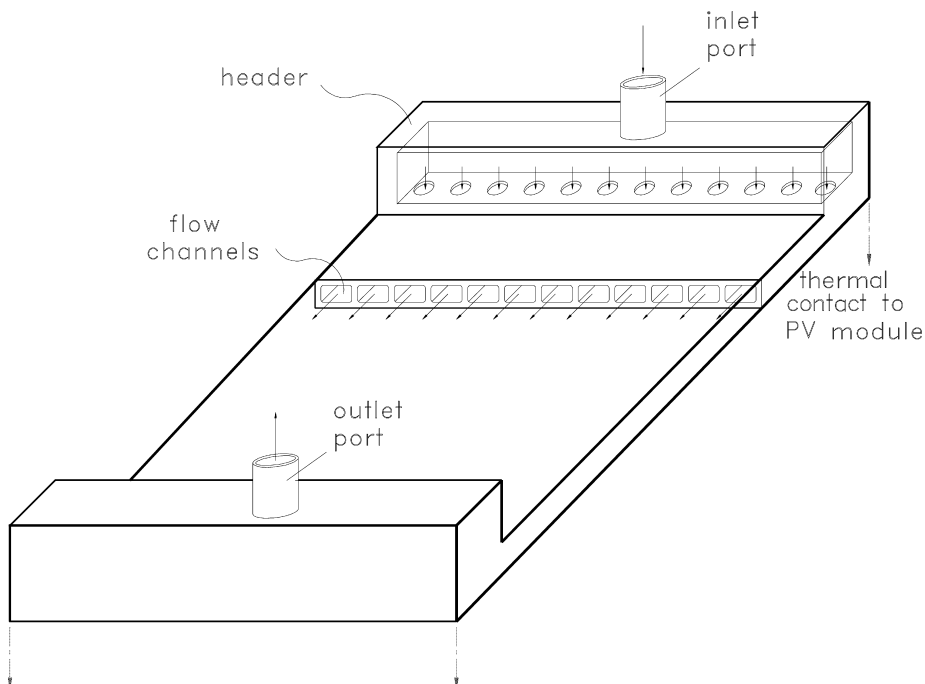


Fig. 3. Schematic diagram of heat-collecting plate.

energy absorption. Under this condition, the pump should be shut down. In a conventional forced-circulation solar hot water system, a DT (differential-temperature) controller controls the pump by sensing the temperature difference between the tank and the exit of the collector. The DC pump was directly controlled by a DT controller (setting 7°C ON and 3°C OFF) using a PC for the experiment.

The water volume stored in the tank in the IPVTS is 45 l, which makes $V_t/A_c = 82 \text{ l/m}^2$. The IPVTS is tested using the testing standard for conventional solar hot water heaters (Huang and Du, 1991). The electrical power generation efficiency of the PV module is 0.09, which is obtained from a separate measurement.

Fig. 4 shows that the temperature of the PV module is very close to that of the water temperature in the tank, within 4°C difference. This means that very good heat transfer is obtained between the PV module and the heat-collecting plate. The water temperature starts to saturate at 15:00 h.

The daily test results are shown in Fig. 5 and Table 1. It can be seen that the primary-energy saving efficiency E_f exceeds 0.60 for cold-start conditions (low initial temperature). As shown in Fig. 5, the characteristic efficiency of the solar PV/T system IPVTS is $\eta_s^* = 0.38$. This is about 76% of the value for a conventional solar hot water heater ($\eta_s^* = 0.50$). This is acceptable since

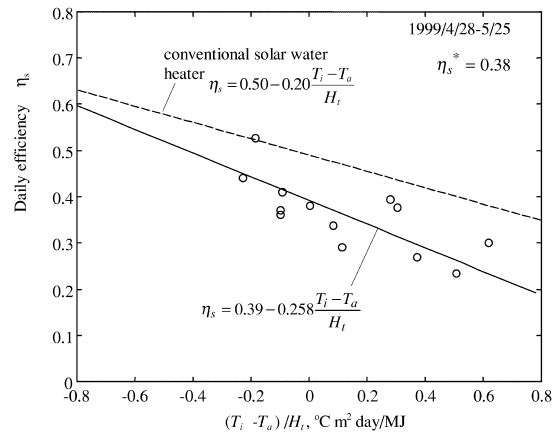


Fig. 5. Daily efficiency test results of IPVTS.

the PV/T collector of the IPVTS is an unglazed collector.

4. DISCUSSIONS AND CONCLUSIONS

In the present study, a commercial polycrystalline PV module is used for making a PV/T collector. The PV/T collector is then used to build an integral-type solar system (IPVTS). We use the testing method for conventional solar hot water heaters for the thermal performance rating of the IPVTS. It is concluded that the solar PV/T collector made from a corrugated polycarbonate panel can obtain a good thermal efficiency, with very similar temperatures (within 4°C difference)

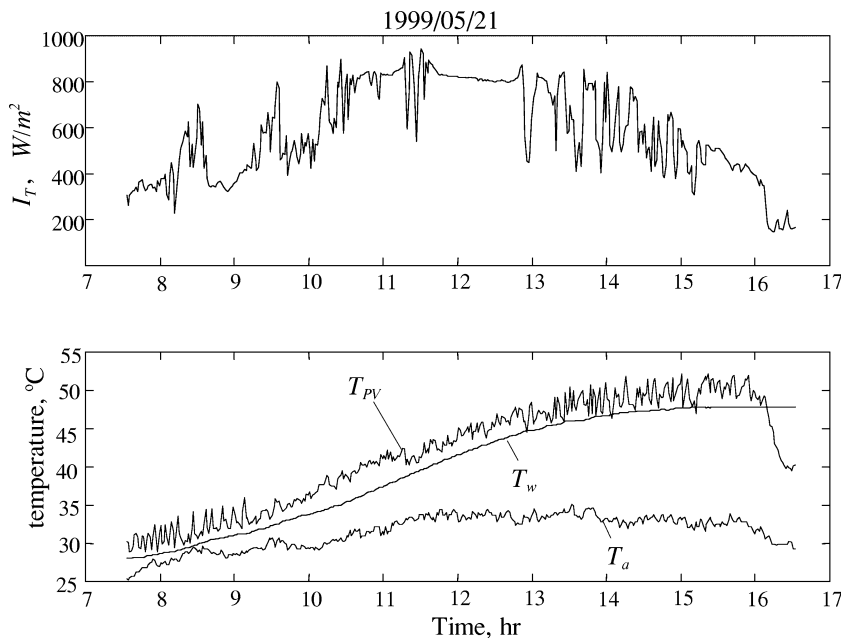


Fig. 4. A test result of IPVTS.

Table 1. Test results of IPVTS ($V_t/A_c = 82 \text{ l/m}^2$)

Date	Daily total	Water temperature		T_a (°C)	Efficiency			
1999	solar radiation	in tank (°C)			η_{th}	η_e	η_o	E_f
	H_i (MJ/m ² day)	Initial T_i	Max					
05/02	6.9	25.4	33.3	25.4	0.385	0.09	0.475	0.622
05/03	7.3	28.1	37.3	28.8	0.411	0.09	0.501	0.648
05/08	15.7	28.2	45.8	29.8	0.372	0.09	0.462	0.609
05/11	15.9	25.7	43.1	27.3	0.363	0.09	0.453	0.600
05/13	12.2	34.5	44.3	30.0	0.271	0.09	0.361	0.508
05/17	10.0	32.9	42.8	32.1	0.337	0.09	0.427	0.574
05/18	15.3	35.7	49.0	34.0	0.291	0.09	0.381	0.528
05/21	15.2	28.0	47.7	31.5	0.445	0.09	0.535	0.613
05/23	9.6	35.0	46.2	32.1	0.376	0.09	0.466	0.613
05/24	9.7	40.0	43.9	31.7	0.122	0.09	0.212	0.359
05/25	6.6	35.3	40.6	29.6	0.232	0.09	0.322	0.469

between the water in the tank and the PV module. Further improvement of the performance of the IPVTS is however possible with good insulation design of the PV/T collector, a better control scheme for the DT controller, and the packaging of the PV module and the heat-collecting plate.

The present study introduces the concept of primary-energy saving efficiency for the evaluation of a PV/T system from the point of view of primary energy gain. The present test results show that the primary-energy saving efficiency of an IPVTS exceeds 0.60, that is, larger than for a pure solar hot water heater or a pure PV system. The characteristic daily efficiency η_s^* reaches 0.38, which is about 76% of the efficiency of a conventional solar hot water heater using a glazed collector ($\eta_s^* = 0.50$).

We chose a commercial PV module for making a PV/T collector since the major purpose of the present study is to understand the performance of an IPVTS as compared to a conventional solar water heater and to demonstrate the idea of an IPVTS design. The present PV/T collector is an unglazed collector and thus has an additional thermal resistance of the silicone-encapsulated EVA material at the back surface and the thermal grease for good thermal contact between the solar PV module and the heat-collecting plate. A lower thermal performance is expected. However, the present test results show that the characteristic daily efficiency η_s^* of the IPVTS is 0.38, which is about 76% of the efficiency of a conventional solar hot water heater using a glazed collector ($\eta_s^* = 0.50$). This indicates that the performance of a PV/T collector can be improved if the heat-collecting plate is in direct thermal contact with the PV cells and the heat-collecting plate is used as the base plate of the PV cells. In addition, the glass cover and the PV cells can be separated to make an air-insulating layer between the glass and solar cells so that the PV/T collector will become

a glazed collector. This design can be easily implemented in the manufacturing process. That is, the PV/T collector actually combines the manufacturing of the PV module and the thermal collector in a single manufacturing process. The manufacturing cost can be reduced. If the PV/T collector is integrated with a storage tank to make an IPVTS, the system cost can also be reduced further. The present study shows that the idea of an IPVTS is economically feasible too.

Finally, we would like to point out that the overall performance of a PV/T system, including thermal and electric conversion, is affected by many factors. The thermal efficiency decreases with increasing hot water temperature. Increasing hot water temperature in order to meet some application requirements would in turn cause the power generation efficiency of solar PV to decrease. Besides, the unit costs of thermal energy collection and electric power generation are different. A new cost function that takes into account the energy gain per unit investment is necessary for system optimization including economic feasibility. A system simulation using meteorological data for a particular design of PV/T system can help to obtain the optimum system design based on the total primary-energy gain per unit investment. This remains for further studies in the future.

NOMENCLATURE

A_c	collector area (taken as PV module area), m ²
D	tube diameter, m
H_t	accumulated solar incident radiation upon collector surface, MJ m ⁻²
T_a	ambient temperature, °C
T_i	initial water temperature in tank, °C
T_{in}	inlet water temperature of PV/T collector, °C
T_f	final water temperature in tank, °C
T_{out}	outlet water temperature of PV/T collector, °C
T_{pv}	temperature of PV panel, °C

T_w	water temperature in the tank, °C
V_t	water storage volume in tank, m ³
V_t/A_c	ratio of water storage to collector area, m ³ m ⁻² or l m ⁻²
W	tube spacing, m
η_s	daily efficiency of solar hot water heater defined by Huang (1993)
η_s^*	characteristic daily efficiency of solar hot water heater defined by Huang (1993)

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