DESIGN OF A DUAL FLOW PHOTOVOLTAIC/THERMAL COMBI PANEL

M. Bakker, H.A. Zondag, W.G.J. van Helden
Energy Research Centre of the Netherlands ECN
P.O. Box 1, 1755 ZG Petten, The Netherlands
phone +31 224 568079, fax +31 224 568966, email *m.bakker@ecn.nl*

ABSTRACT: A prototype of a dual flow photovoltaic/thermal combi panel has been designed and built. In addition, a numerical model of this prototype has been developed, which predicts the thermal efficiency of the prototype. The model predicts a thermal efficiency at zero reduced temperature of $\eta_0 = 0.67$, and a heat loss coefficient of $U_L = 5.3$ Wm^{-2}K^{-1}. The thermal efficiency has also been measured in a combined indoor/outdoor test setup, resulting in measured values of $\eta_0 = 0.70 \pm 0.06$ and $U_L = 5.1 \pm 0.8$ Wm^{-2}K^{-1}. Both values are in good agreement with the model predictions. Finally, the influence of the glass and water layers on the electrical efficiency of the prototype has been measured in a flash test. In conclusion, the dual flow photovoltaic/thermal combi panel has been found to perform as predicted by the model, and with a higher thermal efficiency than other combi panel concepts. However, the concept remains heavy and fragile, and is therefore in its present form not feasible for large scale applications.
Keywords: PV/Thermal, hybrid.

1 INTRODUCTION

A photovoltaic/thermal combi panel, or PVT panel, is a combination of photovoltaic cells with a solar thermal collector, forming one device that converts solar radiation into power and heat simultaneously. The excess heat that is generated in the PV laminate is removed and converted into useful thermal energy. Moreover, the cooling of the laminate effectively increases the PV efficiency.

Because PVT panels have a higher energy output per unit surface area than a combination of separate PV panels and solar thermal collectors, they are especially useful where roof space is limited, like in most residential areas. In addition, the installation cost of a PVT system is potentially much lower than the installation cost of separate PV and thermal systems. Finally, PVT panels have an aesthetic advantage over the combined application of separate PV and thermal systems, due to a more homogeneous roof appearance.

Many different PVT panel concepts exist, varying from building integrated systems with air cooling to flat-plate liquid systems. The present study focuses on the so-called *dual flow* concept. Although its construction is quite complex, the dual flow concept is expected to have the highest thermal efficiency [1].

Figure 1: Schematic overview of the dual flow concept.

The dual flow concept consists of multiple layers of glass and water, a semi-transparent PV layer doubling as primary thermal absorber, and a secondary thermal absorber (see Figure 1). Water flows through the primary channel over the entire surface of the PV laminate, after which it is led back in the opposite direction underneath the laminate. The water is first preheated by the PV laminate, then heated further by the absorber.

The electrical efficiency of a dual flow PVT panel is approximately 15% lower than that of a separate PV laminate, of which approximately 5% is due to absorption in the glass and water layers above the laminate: although the total absorption in the water is much higher, the absorption spectra of water, glass, and silicon are quite different (see Figure 2). The remaining 10% is due to reflection at the glass and water layers.

The thermal efficiency of the dual flow concept is very high, because of the direct contact between the two main absorbing surfaces and the water over the entire irradiated area.

The goal of this work was to build a first prototype of the dual flow concept, to develop a numerical model of the prototype, and to measure its thermal efficiency.

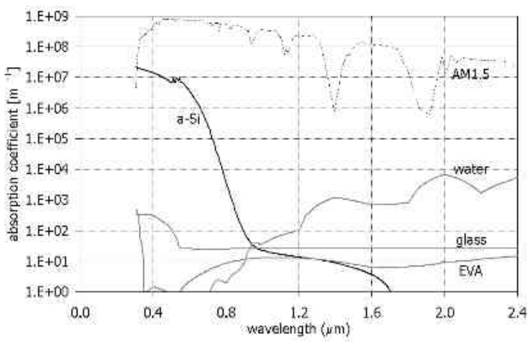

Figure 2: Absorption spectra of the various layers in the PVT panel. It can be seen that the absorption band of amorphous silicon (a-Si) is clearly separated from that of water and glass. For reference, the irradiation spectrum in the Netherlands (AM1.5) is shown in arbitrary units.

2 PROTOTYPE CONSTRUCTION

A prototype of the dual flow concept has been constructed, using a semi-transparent amorphous silicon *pin–pin* module, laminated between two tempered glass sheets of 600×1000 mm^2. Although this module was primarily selected for very practical reasons—it could be delivered within the required timeframe—preliminary calculations have shown that the selection of PV material has an influence on the thermal efficiency of less than 0.5% [2].

For the channel cover, tempered glass has been used, as it is highly transparent in the visible and UV. In addition, it is very rigid, temperature resistant, and watertight. However, because glass is also quite brittle, an 8 mm thick—and over 10 kg heavy—glass sheet was required to withstand the water pressure in the channels. Alternatively, plastic sheets (such as PC or PMMA) could have been used, but they would have to be reinforced in some way to prevent them from bending too much under the water pressure. Moreover, plastics are generally less transparent than glass, and suffer from degradation under influence of UV and high temperatures.

The water channels have been kept at a fixed thickness of 2 mm using aluminium spacers, and have been sealed using a silicone adhesive. The construction has been designed to withstand a temperature of 85°C and a water pressure of 0.2 MPa with a safety factor of 2, enough to sustain a flow of 30 lh^{-1} [2].

The prototype has been placed in an insulated aluminium box with a single glass cover, comparable to a typical solar thermal collector. As this box was slightly larger than the prototype, all but the aperture area of the collector has been covered with reflective foil, to ensure that only irradiation on the prototype itself would contribute to its performance.

3 NUMERICAL MODEL

In order to predict and understand the performance of the dual flow PVT prototype, a numerical model has been developed, consisting of an optical and a thermal model.

In the optical model, the total net reflection, transmission, and absorption are calculated for each layer of the panel, using the net radiation method [3]. The model assumes unpolarized, perpendicular irradiation and specular reflections. Given the total irradiation and the thickness and absorption coefficient of each layer, the optical model calculates the total amount of absorption in each layer of the panel.

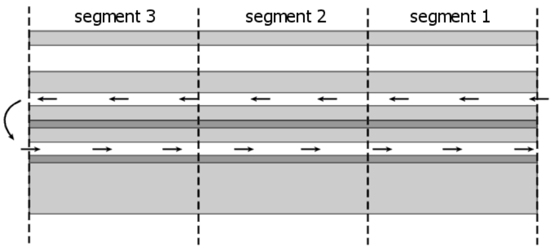

Figure 3: Schematic representation of the thermal model. The panel is divided into three segments; for each segment a system of heat balance equations is solved.

In the thermal model, the thermal efficiency of the prototype is calculated from a system of heat balance equations. To simulate the flow of water through the channels, the panel is divided into three segments (see Figure 3; more segments do not improve accuracy [1]). For each segment, the heat balance is solved: the water outflow temperature of one segment is used as water inflow temperature of the next. Because the temperatures of the primary and secondary water channels influence each other, the heat balance for the panel has to be solved iteratively.

The heat balance consists of absorption of irradiance in each layer; radiative, convective, and conductive losses to the ambient; radiative and convective transfer in the insulating air layer; heat conduction through each layer; and heat exchange between adjacent layers. Electricity production in the PV layer is taken into account as well.

The thermal efficiency curve as predicted by the numerical model is shown in Figure 5.

4 MEASUREMENTS AND RESULTS

Similar to that of a solar thermal collector, the thermal efficiency of a PVT panel is defined as

$$\eta = \frac{\dot{m} c_p \left(T_{out} - T_{in}\right)}{A G_{py}}, \qquad (1)$$

where $\dot{m}$ is the mass flow of water through the panel, c_p is the heat capacity of water, T_{out} and T_{in} are the out- and inlet temperatures, respectively, A is the aperture area, and G_{py} is the irradiation as measured by a pyranometer.

The thermal efficiency is usually expressed in terms of the more practical quantities η_0, being the thermal efficiency when the inlet temperature is equal to the ambient temperature, and U, a heat loss coefficient:

$$\eta = \eta_0 - U T^*. \qquad (2)$$

Here, the reduced temperature T^* is introduced, which is defined as the difference between the water temperature at the panel inlet and the ambient temperature, normalized to the irradiation:

$$T^* = \frac{T_{in} - T_{amb}}{G_{py}}. \qquad (3)$$

Combination of equations (1), (2) and (3) yields the following expression for U:

$$U = \frac{m c_p}{A} \frac{\left(T_{in} - T_{out}\right)}{\left(T_{in} - T_a\right)}$$

The thermal efficiency at zero reduced temperature η_0 and the heat loss coefficient U have been determined in two separate measurements: the former in an outdoor test setup, the latter in an indoor measurement.

For the outdoor measurement, the prototype has been placed on a southward facing roof at 45° inclination (see Figure 4), and a steady water flow of 30 lh^{-1} was led through the panel with an inlet temperature equal to the ambient temperature. By measuring only at low wind speeds ($v_{wind} < 2\ ms^{-1}$), high irradiation ($G_{py} > 750\ Wm^{-2}$) and after all temperatures have stabilized ($\Delta T < 0.2$ K), a steady state condition of the panel has been ensured. In this steady state, an efficiency of $\eta_0 = 70\% \pm 6\%$ has been measured.

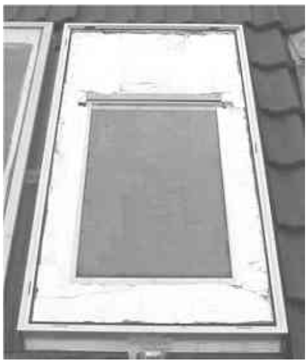

Figure 4: Photograph of the prototype of a dual flow PVT panel, as installed in the outdoor test setup.

Next, the heat loss coefficient U has been determined in an indoor heat loss measurement. This time, the prototype has been placed indoors, where it was shielded from irradiation ($G_{py} < 2$ Wm^{-2}). A water flow of 30 lh^{-1} with an inlet temperature of 60°C was led in reversed direction through the panel. By measuring the in- and outlet temperature and the ambient temperature, again in a steady state condition, the heat loss coefficient has been found to be $U = 7.0 \pm 0.8$ Wm^{-2}K^{-1}.

Because this measurement was performed indoors, radiative heat losses were underestimated, as the radiation temperature of the sky is typically 15 K lower than the ambient temperature. Although this strongly affects the value of η_0, the measurement error in U due to this effect has been estimated using the numerical model described above, and has been found to be less than 0.5%.

An additional correction must be applied to this heat loss measurement, as aluminium U-profiles have been used to reinforce and protect the prototype construction, that have not been included in the model. These profiles increase the effective surface area of the prototype by approximately 27%. In first order, the heat loss is proportional to this surface area. Correcting for the extra heat loss due to these U-profiles, the measured heat loss coefficient is $U_L = 5.1 \pm 0.8$ Wm^{-2}K^{-1}.

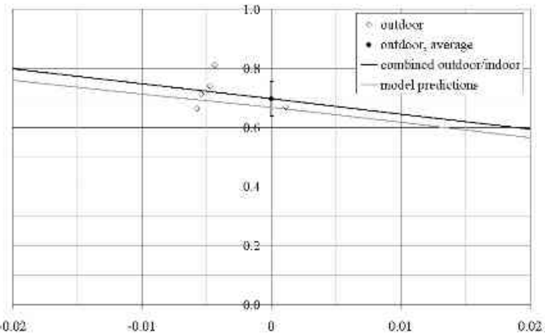

Figure 5: Comparison of the measured and predicted thermal efficiency as a function of T^*. The out- and indoor measurements have been combined to yield the black curve: its offset is determined by η_0, resulting from the outdoor measurements; its slope is determined by U_L, resulting from the indoor measurements.

The results of the outdoor and indoor experiments have been combined to yield the efficiency curve shown in Figure 5.

In addition, the influence of the glass and water layers on the electrical efficiency of the PV laminate has been tested by measuring its short circuit current in a flash test. For an uncovered laminate, a short circuit current of 1.16 A has been found. When covered with an 8 mm glass sheet above an air gap of 2 mm, the short circuit current falls to 1.01 A, a decrease of 13%. When the air gap is filled with water, the short circuit current recovers to 1.09 A, 6% lower than the uncovered laminate. This recovery is due to the fact that the refractive index of water more closely matches that of glass, strongly decreasing reflection losses. These numbers correspond to the expectations expressed in the introduction.

5 DISCUSSION

As can be seen in Figure 6 and Table I, both the outdoor and indoor measurement results are in good agreement with the model predictions. Although η_0 was found to be slightly higher than predicted by the model, the model prediction falls well within the measurement error. In addition, the heat loss coefficient U_L was initially found to be higher than predicted, but when corrected for extra heat losses due to reinforcing profiles in the prototype, its measurement is in good agreement with the model predictions.

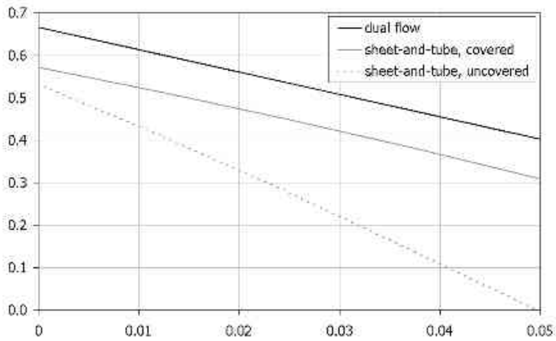

Figure 6: Thermal efficiency as a function of T^* of the dual flow concept, compared to the covered and uncovered sheet-and-tube concept [4].

Table I: Comparison of numerical model predictions with measurement results.

	η_0	U_L [Wm^{-2}K^{-1}] (at 60°C)
Numerical model	0.67	5.3
Measurements	0.70 ± 0.06	7.0 ± 0.8
Corrected measurements	0.70 ± 0.06	5.1 ± 0.8

Compared to other PVT concepts, the dual flow concept is found to perform very well. A comparison of the dual flow concept with two other concepts is shown in Figure 6. Roughly, both concepts consist of crystalline silicon cells, fixed to a sheet-and-tube absorber; the covered sheet-and-tube PVT concept is enclosed in an insulated box with a glass cover, similar to the dual flow concept; the uncovered sheet-and-tube PVT panel has less insulation and is not covered. It can be seen that the dual flow concept has the highest efficiency at zero reduced temperature and the lowest heat loss coefficient.

Despite its excellent thermal performance, the dual flow concept remains very heavy and fragile due to the large amounts of glass required. This strongly reduces its feasibility for large scale applications.

A modified concept with only one channel below the PV laminate, possibly in the form of a channel sheet, would greatly simplify the construction, yet retain a very high thermal efficiency.

REFERENCES

[1] Vries, D.W. de, *Design of a photovoltaic/thermal combi-panel*, PhD-thesis Eindhoven University of Technology, 1998.

[2] Bakker, M., *Design of a dual flow photovoltaic/thermal combi panel*, MSc-thesis Eindhoven University of Technology, 2002.

[3] Siegel, R., *Net radiation method for transmission through partially transparent plates*, Solar Energy 15, pp. 273–276, 1973.

[4] Zondag, H.A., Jong, M.J.M., Helden, van, W.G.J., *Development and applications for PV thermal*, 17th PVSEC, Munich, 2001.