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Maximising the energy output of a PVT air system

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Abstract

Simultaneously generating both electricity and low grade heat, photovoltaic thermal (PVT) systems maximise the solar energy extracted per unit of collector area and have the added benefit of increasing the photovoltaic (PV) electrical output by reducing the PV operating temperature. A graphical representation of the temperature rise and rate of heat output as a function of the number of transfer units *NTUs* illustrates the influence of fundamental parameter values on the thermal performance of the PVT collector. With the aim of maximising the electrical and thermal energy outputs, a whole of system approach was used to design an experimental, unglazed, single pass, open loop PVT air system in Sydney. The PVT collector is oriented towards the north with a tilt angle of 34°, and used six 110 Wp frameless PV modules. A unique result was achieved whereby the additional electrical PV output was in excess of the fan energy requirement for air mass flow rates in the range of 0.03–0.05 kg/s m^2. This was made possible through energy efficient hydraulic design using large ducts to minimise the pressure loss and selection of a fan that produces high air mass flow rates (0.02–0.1 kg/s m^2) at a low input power (4–85 W). The experimental PVT air system demonstrated increasing thermal and electrical PV efficiencies with increasing air mass flow rate, with thermal efficiencies in the range of 28–55% and electrical PV efficiencies between 10.6% and 12.2% at midday.

Keywords: Photovoltaic thermal; PVT air system; PVT collector; Number of transfer units; Whole of system

1. Introduction

Hybrid photovoltaic thermal (PVT) systems produce both electricity and low grade heat. Typically they utilise either air or water as the fluid to extract the heat from the photovoltaic (PV) panels. The attractiveness of PVT systems is that the electrical output of the PV panels as well as the quantity of heat increases as the mass flow rate of the fluid increases. However, these gains are offset by (i) the temperature rise of the fluid through the collector decreasing and (ii) the electrical energy required for the pump or fan moving the fluid through the PVT system increasing, as the mass flow rate increases. Design of a PVT system therefore involves a balance of the fundamental parameter values (such as the air mass flow rate, collector area, and channel depth) to obtain the required outputs for a particular climate. The focus of this paper is an open loop PVT air system as it is thought to have significant potential for roof integration in a Sydney house.

The most common PVT air collector design consists of an air duct directly beneath a photovoltaic array, however a number of different designs for PVT air collectors have been explored through both theoretical analysis and experimentation. Various PVT air collector designs have been presented in the literature with some of the main features implemented being single-pass or double-pass air flow, using fins or channels in the duct, and using the PVT concept as either a building wall façade or a roof mounted unit (Hegazy, 2000; Tonui and Tripanagnostopoulos, 2007; Eicker and Gross, 1997; Hollick and Barnes, 2007; Chen

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et al., 2010). PVT air collectors can also be covered or uncovered, where a covered collector has an additional glass cover over the photovoltaic modules to reduce heat loss from the top of the collector (Tonui and Tripanagnostopoulos, 2007; Garg and Adhikari, 1997).

The last 10 years has seen an increase in the published work on experimental PVT systems. Experimental investigations on PVT air systems have been primarily conducted in colder climates such as Europe and Canada (Tonui and Tripanagnostopoulos, 2007; Chen et al., 2010; Mei et al., 2009; Candanedo et al., 2010). Tonui and Tripanagnostopoulos (2007) investigated low cost improvements for PVT air collectors to enhance the heat extraction from the PV module. Their results showed that the best thermal and electrical performance was achieved by the PVT collector with fins in the duct. The PVT collectors with a glass cover exhibited higher thermal efficiencies but lower electrical efficiencies compared with the uncovered collectors. The reduction in electrical efficiency was attributed to greater absorption and reflection losses due to the glass cover and the higher PV module temperature.

Candanedo et al. (2010) compared their general steady state and transient PVT air collector models with experimental data from an experimental facility at Concordia University. PVT test channels, consisting of an amorphous silicon PV module glued to a 0.5 mm stainless steel absorber sheet, formed the top of the channel, with the remainder of the channel being constructed from plywood and polystyrene insulation with an R-value of 1.76 m^2 K/W. The transient model demonstrated a better match to the measured data compared with the steady state model as the effect of the air temperature fluctuations on the transient model were reduced due to the thermal capacitance effect which decreased the sensitivity of the model to variations in irradiance and wind speed.

Chen et al. (2010) investigated a BIPVT system thermally coupled with a ventilated concrete slab in a low energy solar house located in the cold climate of Quebec, Canada. The BIPVT system consists of 21 amorphous silicon 136 W PV modules bonded directly to metal roofing which covers an area 6.2 m long and 10.4 m wide. A shallow air duct with a depth of 0.038 m runs underneath the metal roofing and the back of the channel is composed of plywood and insulation. The use of low air flow rates (0–0.0056 kg/s m^2) enables large temperature increases between the inlet and outlet air of the order of 40 °C for a sunny day in winter. The PV modules were shown to be operating at high temperatures around 50–60 °C under these conditions. A typical thermal efficiency of 20% for the BIPVT system was reported.

In the warmer Sydney climate, Bazilian (2002) conducted testing of an experimental building integrated photovoltaic thermal (BIPVT) air system. An air temperature rise (T_{out}–T_{in}) of between 2 and 6 °C and a reduction of between 5 and 9 °C in the PV cell operating temperature was achieved with an air flow rate of ~0.02 kg/s m^2 during winter. The fan power was reported to be 4–6 W. Based on the result of an average daily thermal energy production of 0.87 kWh/m^2/day in winter, it was recommended that the PVT system should not be designed to fully cover the space heating load of a house, but to augment a smaller auxiliary heating system.

Research to date has largely focused on the PVT air collector itself, rather than the whole PVT air system. Various PVT air collector designs and performance improvements have been investigated by numerous authors, however, whole system aspects such as the duct sizing and the fan power requirement have not been widely reported. The fan power requirement is an important consideration in a PVT air system and the calculated values presented in the literature vary widely (Tonui and Tripanagnostopoulos, 2007; Chen et al., 2010; Candanedo et al., 2010). There is also very little information available on the quantified additional electricity generated by the PVT air system at different air flow rates and this work investigates whether this additional electrical energy is greater than the fan power requirement.

In this paper, key thermal performance indicators are examined to determine the PVT collector design suited to the climate. An experimental PVT system designed to maximise energy output in the Sydney climate is then presented. Finally, experimental results illustrate the thermal, electrical and whole system performance.

2. PVT collector design

In this section, the relationship between the heat output and the temperature rise of a PVT collector is examined by considering the fundamental parameters that determine the collector's performance.

2.1. Relationship between heat output and temperature rise

For a photovoltaic thermal (PVT) collector, the important outputs are the outlet fluid temperature, the heat output, and the electrical output. The desired outlet fluid temperature will determine the operating temperature of the PV cells and therefore the electrical output of the PVT collector. Previous research has demonstrated that there is a trade-off between the outlet fluid temperature, the heat output, the fluid mass flow rate and the electrical output (Tonui and Tripanagnostopoulos, 2007; Sopian et al., 1996; Shahsavar and Ameri, 2010; Tiwari et al., 2006).

The approach presented by Duffie and Beckman (2006) is the most commonly used approach for describing the relationship between the heat output and temperature rise for a solar thermal collector. Duffie and Beckman (2006) discuss the following five terms.

1. The heat removal factor (F_R) which is equivalent to the effectiveness of a conventional heat exchanger, which is given by,