Simulation of a concentrating PV/thermal collector using TRNSYS

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Abstract

A TRNSYS component (Type 262) has been written to simulate a concentrating PV/Thermal collector. The component is based on a dynamic model of a concentrating PV/Thermal collector, which includes thermal capacitance effects, and detailed equations describing the temperature dependent energy flow between the collector and surroundings. The CHAPS system, a 30x concentration parabolic trough PV/Thermal collector developed at the ANU, has been used to validate the accuracy of the Type 262 TRNSYS component. Results are presented comparing the annual output of a domestic CHAPS system that integrates the Type 262 collector, with a flat plate solar hot water system and a PV array located side-by-side.

1 Introduction

The Combined Heat and Power Solar System, or CHAPS system being developed at the Australian National University, is a concentrating parabolic trough system that combines photovoltaic (PV) cells to produce electricity, with thermal energy absorption to produce hot water. The current status of the CHAPS project is described in Coventry et al. (2002) as well as details about the major components of the system and preliminary performance data. This paper outlines a theoretical model of the collector, and shows some early validation results. Further validation is necessary, particularly because electrical performance data has not yet been available. With this proviso, the component has been integrated into a full domestic hot water system model that includes a hot water tank, pump, controller, weather data and water draw-off profile. Early results of simulations are presented.

2 The PV/T TRNSYS component

TRNSYS is a transient simulation package used extensively to model solar systems, in particular heating, cooling and domestic hot water applications (Solar Energy Laboratory, 2000). TRNSYS relies on a modular approach to solve large systems of equations described by Fortran subroutines. Each Fortran subroutine (called a *type*) contains a model for a system component. A detailed analytical PV/Thermal TRNSYS component has been written (Type 262), based closely on the equations outlined in this paper. Further technical detail about the component can be found in the ANU reference manual (Coventry et al., 2001). There have been other PV/T models written, such as the Type 50 PV/Thermal collector available in the standard TRNSYS library. This model is based on modifications to the Hottel-Whillier-Bliss equations that are used for the standard Type 1 Flat Plate Solar Collector (Florschuetz, 1979) however it does not account for radiation losses and has no thermal capacitance, and is therefore not considered to be detailed enough to simulate a CHAPS collector. It is also an empirical model and therefore it is difficult to model variations in physical subcomponents of the PV/T collector. A flat plate PV/T model is also under development at the Danish Teknologisk Institut (Bosanac, 2001).

3 Theoretical Formulation

A dynamic model of a concentrating PV/T collector has been developed in order to simulate both thermal and electrical performance. The equations describe the thermal performance with reasonable precision However the electrical performance is much simplified, and is discussed in further detail in Coventry et al. (2002). The CHAPS receivers are made up of solar cells mounted on an aluminium extrusion bonded to a copper pipe containing the heat transfer fluid, as shown in Figure 1. Figure 2 shows the reference system for the dynamic model.

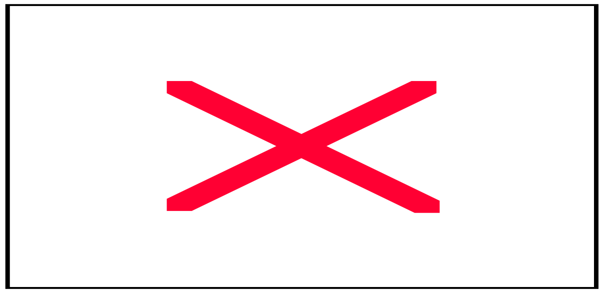


Figure 1. Cross-section of a CHAPS receiver.

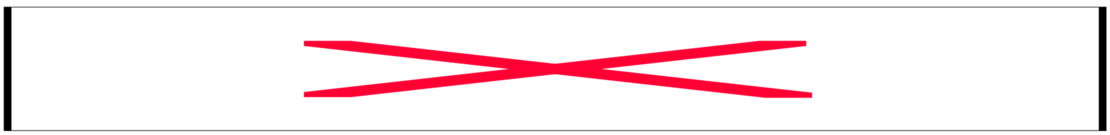
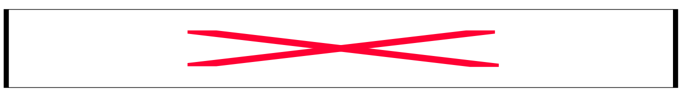


Figure 2. Reference system for the thermal model of a CHAPS receiver.

Equation 1 describes the change in temperature of the fluid in the receiver with respect to time:



(1)

where , , and are the mass and specific heat terms for the collector and the fluid, is the fluid mass flow, and are the outlet and inlet fluid temperatures, and is the energy flow.

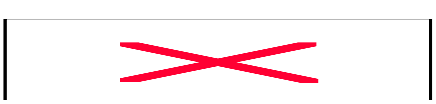
The temperature and illumination gradients perpendicular to the flow, and the conductive heat transfer parallel to the flow are neglected. The collector is divided up into a series of elements along its length. In the case of a concentrating collector, it is convenient to divide the collector up by elements of length equal to that of a solar cell. It is assumed that each element can be characterized by a single temperature T. Equation 1 is derived from the energy balance of a control element, taking into account:

- The change in energy content of the element
- The energy transfer by the fluid flow
- The temperature dependent energy flow between the element and surrounding,
- A line heat source.

Although the thermal energy flow is a function of temperature, which changes with time, a numerical approach to the solution of the equation is to base the calculation of on the temperature of the element a short time earlier. Therefore, equation 1 can be rearranged to form a first order differential equation. This method of solution of the energy balance equation is suggested in the TRNSYS reference manual (Solar Energy Laboratory, 2000) for components with a temperature response dependent on time.

(2)

Solving for T with respect to time t allows an average outlet temperature over some small time interval of t to t+_t, to be calculated by integrating the outlet temperature:



(3)

where $T_{initial}$ is the outlet temperature at a starting time t.

The value of can be calculated by solving a set of non-linear equations that physically describe the temperature dependent energy flow between the element and the surroundings. The thermal network describing this arrangement is shown in figure 3.

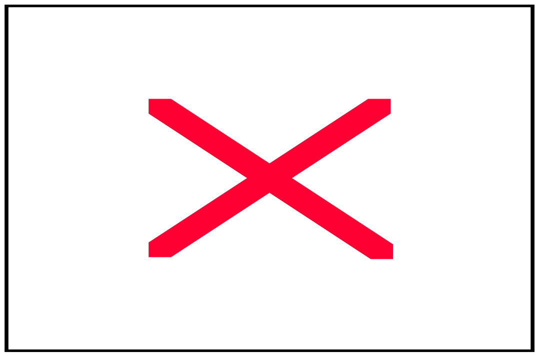


Figure 3: Thermal network describing a PV/T concentrating collector.

The main terms of the energy balance are described below:

Sun input **:** total direct radiation I_d absorbed by the solar cells as reflected by the mirror area A_{mirror}, including transmissibility of the glass cover , and absorptivity of the solar cells . It also includes scaling factors for the accuracy F_{shape} and reflectivity of the concentrator, the shading of the mirrors F_{shade}, and the dirtiness of the mirrors F_{dirt}.

(4)

Thermal output : the energy transferred into the water (not including the effect of thermal capacitance). U_{pt} is the heat transfer coefficient between plate and tube, and A_{pt} the area of contact. T_{tube} and T_f are the temperatures of the tube and fluid respectively, and A_{tf} the surface area of the inside of the tube. The convection coefficient h_{cw} is defined below.

(5)

Electrical output : derived from the simplified maximum power output expression given in Wenham et al. (1994). Sometimes a simpler linearised relationship is used, however this becomes more inaccurate at the higher temperatures possible with a concentrating PV/T collector. The reference efficiency is measured at a reference temperature T_{ref}, usually 25°C. is the temperature coefficient giving the relationship between solar cell efficiency and temperature (around –0.004 for silicon solar cells), and T_{cells} the temperature of the solar cells.

(6)

Radiation loss ; glass is opaque to radiation emitted from the cells, and therefore the cover glass becomes the emitting surface. is the Stefan-Boltzmann constant, $_{glass}$, A_{glass} are the emissivity and area of the glass cover, T_{glass} the temperature of the outer surface of the glass, and T_{amb} is the ambient temperature. It is assumed that the surroundings are at ambient temperature.

(7)

Convection loss : can be calculated analytically (see for example Duffie and Beckman (1974)). However, a simpler empirical approach is used, where is the convection coefficient, is the wind speed and c_0, c_1, and c_3 are coefficients derived by parameterisation studies described in Section 4. The significance of wind speed dominates other factors such as the tilt of the receiver.

(8)

where (9)

Loss through the insulation : it is assumed that the heat transfer coefficient U_{ins} remains reasonably constant within the range of operating temperature and that the insulation thickness is uniform. A_{ins} is the area of insulation, and T_{plate} is the temperature of the absorber plate surrounded by the insulation. It is assumed that the temperature difference between the outer cover and ambient is very small, and therefore detailed calculations of convection and radiation losses from the cover are unnecessary.

(10)

Convection coefficient between the tube and the fluid $h_{c\text{-}w}$: this changes significantly, depending on whether or not the fluid flow in the pipe is laminar or turbulent. Empirical relations describing how the convection coefficient can be calculated can be found in Holman and White (1992), Incropera and DeWitt (1990), and similar texts. The mass flow is reasonably constant for the application described in this paper, and therefore to simplify the calculation in the model, the convection coefficient is entered as a parameter in the TRNSYS model and assumed to be constant along the receiver.

Other relationships required to determine are:

(11)

(12)

(13)

where and are the energy transfers from solar cells to the plate and glass cover respectively. U_{cp}, U_{cg}, A_{cp} and A_{cg} are the heat transfer coefficients and areas of the cell-plate and cell-glass interfaces respectively.

4 Validation

Experimental validation of the PV/T component has commenced, but is yet to be finalised. The validation work thus far has focused on thermal output, as experimental data for electrical output power has not been available. Data from a number of sunny days with a range of input conditions measured at three-minute intervals were selected, and system parameters that were easy to measure (such as mirror dimensions, solar cell area, etc) were fixed in the model.

Other parameters, such as the coefficients determining the relationship between wind speed and convection losses, were found by parameterisation techniques using GenOpt, which is a generic optimisation program developed at the Lawrence Berkeley National Laboratory (Wetter, 2000). An objective function was defined in TRNSYS based on the difference between the predicted and measured thermal output. GenOpt was then used to minimise this function by running the Nelder-Mead-O'Neill algorithm to vary the selected parameters.

Figure 4 shows the plot of predicted and measured thermal energy and outlet temperature for the compiled data. The large spikes are not real as they relate to the changeover time steps between different data sets. These spikes and other anomalies are filtered out for the purposes of the parameterisation with GenOpt. The results for this seem accurate when the outlet temperatures are compared, however the thermal energy outputs show that a small difference in output temperature results in a significant difference in thermal energy flow.

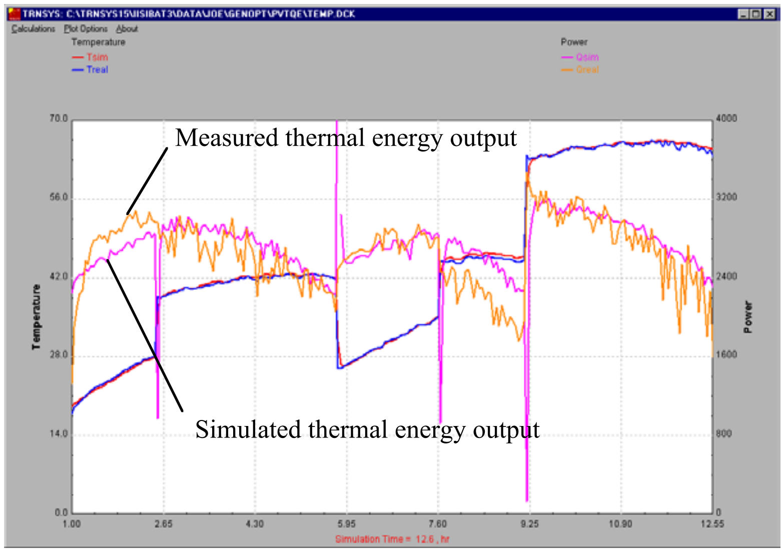


Figure 4. TRNSYS output window showing simulated and measured thermal energy output. The concurrent lines show the measured and simulated output temperature.

Further work will be carried out to gather more data from a range of weather and inlet conditions and fine-tune the PV/T component where necessary to improve the accuracy of the model.

4.1 Domestic CHAPS system model

A simulation has been built that models the first domestic CHAPS system prototype located on a mock-up roof at the Faculties Teaching Centre at the ANU (described in detail in Coventry et al. (2002)). The model includes two CHAPS collectors, a tank, a demand profile, and shading losses. The simulation compares the CHAPS system to a solar hot water system of an equivalent size mounted on the same roof, using two Solahart Type K black chrome collectors modeled with the Type 1 TRNSYS component. Data about the efficiency of these collectors is obtained from the Solar Rating and Certification Corporation (2000). The CHAPS system is also compared to an equivalent sized photovoltaic array, based on three high-efficiency BP5170 modules, and modeled using the TRNSYS Type 94 component.

Weather data for Canberra compiled by the University of NSW (Morrison and Litvak, 1988) was used for all three systems. The data is a compilation of months from different years, chosen such that they reflect long-term averages for the particular month. The hot water demand profile for the CHAPS and Solahart systems was based on an energy draw profile set out in the Australian Standards AS4234-1994. A Solahart Streamline tank is modeled using a Type 140 tank with 10 thermal zones, a thermostat set to 60°C, and a 3.6kW auxiliary heating element, in the second and third zone from the top of the tank respectively. The UA-value was 2.27 W/K for the 300L tank. The tank employs simple 'delta T' control, with the over-temperature cutoff set to 95°C. Shading of the rear mirror is calculated using equations particular to the geometry of the CHAPS system .

Solar energy fraction is used as a measure of annual thermal performance, defined as $1 - Q_{aux}/Q_{dem}$, where Q_{aux} is the auxiliary energy use in heating water and Q_{dem} is the annual hot water demand. As indicated in table 2, the performance of the CHAPS system annually compares very well with both the flat plate hot water collector and the PV array.

System	Hot water demand	Auxiliary energy use	Electrical energy generated	Incident radiation	Solar hot water energy fraction	Annual electrical efficiency
	kWh/year	KWh/year	KWh/year	kWh/year		
Photovoltaic array			842	7,206		11.7%
Solar hot water system	3,486	1,434		7,206	58.9%	
CHAPS system	3,486	1,480	780	7,883	57.6%	9.9%

Table 2. Comparison of the CHAPS system with conventional solar hot water and PV systems

The primary motivation for a CHAPS system is to bring down the cost of both renewable electricity and hot water. Therefore, given that the annual output of the CHAPS system is similar to separate flat plate PV and solar hot water systems*, savings could be achieved if the cost of the system is lower than the sum of cost of the separate systems. Early cost estimates for the CHAPS system are positive in this regard, however further cost information will not be available until the first 30 systems are installed in the coming 12 months as part of a broader trial supported by the Sustainable Energy Development Authority of NSW. Significant roof space savings are also achieved, with the CHAPS system occupying around half the area of equivalent sized separate PV and solar hot water systems.

5 Conclusion

A simulation model of the CHAPS collector has been developed based on analytical equations describing the thermal and electrical performance of a concentrating PV/Thermal collector. The collector model has been integrated into a full domestic CHAPS system model to show that the annual thermal energy output is similar one of the best available flat plate solar hot water collectors, and the annual electrical energy output is similar to one of the highest efficiency available PV modules.

6 Acknowledgements

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7 References

Bosanac, M., 2001. Teknologisk Institut, Denmark, Personal communication

Coventry, J., Kreetz, H., and Dennis, M., 2001: Technical manual - TRNSYS Components developed at the ANU.

Coventry, J., Franklin, E., and Blakers, A., 2002: Thermal and electrical performance of a concentrating PV/Thermal collector: results from the ANU CHAPS collector. *ANZSES Solar Energy Conference*, Newcastle.

Duffie, J. A. and Beckman, W. A., 1974: *Solar energy thermal processes*. 1st Edition ed. John Wiley & Sons Inc

Florschuetz, L. W., 1979: Extenssion of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors. *Solar Energy*, **22,** 361-366.

Holman, J. P. and White, P. R. S., 1992: *Heat Transfer*. 7th ed. McGraw-Hill Inc.

Incropera, F. P. and DeWitt, D. P., 1990: *Fundamentals of heat and mass transfer*. 3rd ed. John Wiley & Sons.

Solar Energy Laboratory, 2000: TRNSYS Reference Manual, University of Wisconsin-Madison

Morrison, G. and Litvak, A., 1988: Condensed Solar Radiation Data Base for Australia Report 1, Solar Thermal Energy Laboratory, University of NSW, 13 pp.

Solar Rating and Certification Corporation, 2000: *Directory of SRCC Certified Solar Collector and Water Heating System Ratings*.

Wenham, S. R., Green, M. A., and Watt, M. E., 1994: *Applied Photovoltaics*. Centre for Photovoltaic Devices and Systems, University of NSW, 290 pp.

Wetter, M., 2000: *GenOpt Generic Optimisation Program*. Lawrence Berkeley National Laboratory.