A Combined Optical, Thermal and Electrical Performance Model of a Building Integrated Photovoltaic/Thermal Concentrator (BIPVTC)

T N Anderson
School of Engineering
Auckland University of Technology
Auckland, New Zealand
Email: timothy.anderson@aut.ac.nz

R Künnemeyer, M Duke, J K Carson
School of Engineering
University of Waikato
Hamilton, New Zealand
rainer@waikato.ac.nz, dukemd@waikato.ac.nz,
j.carson@ waikato.ac.nz

Abstract—**The electrical output of concentrating photovoltaic devices is significantly affected by the temperature of the photovoltaic cells. The ability to actively cool photovoltaic cells under concentrated radiation allows their electrical efficiency to be maintained particularly during periods of high solar radiation when concentration offers the maximum benefit. In this study, the design of a novel photovoltaic/thermal solar concentrator for building integration (BIPVTC) is discussed. The optical, thermal and electrical performance of the collector was theoretically modelled and validated with experimental data. The results show that BIPVTC offers improved electrical yields from both concentrating radiation onto the photovoltaic cells and also by actively cooling them.**

Keywords-component; photovoltaics, solar concentrator, cooling, BIPVT-C

I. INTRODUCTION

In recent times there has been an increased interest in the development of Photovoltaic/Thermal (PVT) solar energy systems that generate both thermal and electrical energy [1-3]. One particular area of development is building integrated PVT (BIPVT) systems.

In essence, BIPVT is the embodiment of PVT in building elements such as roofing or façades. Considering the vast majority of solar panels are used in an urban environment using BIPVTs for cogeneration is a means of achieving higher energy generation density (kWh/m^2). Additionally, integration minimises the detrimental visual impact of conventional solar systems in the built environment. Perhaps most importantly the energy output of the photovoltaic cells could be improved with cooling while supplying thermal energy for hot water and/or space heating.

There are however shortcomings in existing BIPVT systems: in particular a comparatively high cost by virtue of the use of photovoltaics. A potential solution to this shortcoming is to develop BIPVT collectors which incorporate concentrators to increase the output from the photovoltaics using lower cost material.

Tripanagnostopoulos et al. [2] discussed perhaps the simplest incarnation of a concentrating PVT concentrator. In their system they used a reflector plate to direct extra solar radiation onto a PVT collector giving a concentration ratio of approximately 1.3. They found that the use of this simple concentrator increased the thermal efficiency of their PVT collector from 38% to approximately 60%.

Similarly, concentration of solar radiation can also be achieved with compound parabolic concentrators (CPC), linear or circular Fresnel lenses, or reflectors with parabolic dishes. Garg and Adhikari [4] demonstrated the use of several truncated CPCs in a single PVT module. They found that their collector for air heating, with a concentration ratio of 3, resulted in better efficiencies when integrated into a system.

As mentioned, concentration by linear Fresnel reflectors is also possible. Rosell et al. [5] demonstrated a system based on this method that had a concentrating ratio of 11. They were able to obtain a maximum thermal efficiency of approximately 60% from their system with no electrical load. Another variation on linear focusing PVT collectors was the CHAPS (concentrating heat and power system) discussed by Coventry [6], which used a parabolic trough reflector with a PVT module mounted at its focus. The system had a concentration ratio of 37 and had a maximum reported combined efficiency of 69%.

The principal shortcoming of all these studies however was that none considered how such systems might be integrated into buildings to form a BIPVT-concentrator (BIPVTC). A solution to this may be to develop simple V-trough style concentrators that lend themselves to easy fabrication. An early study by Bannerot and Howell [7] had suggested that static V-trough collectors could achieve an annual average concentration ratio of over 1.2 for locations with a high diffuse solar fraction, and might be suited to applications where the reflectors were offsetting the cost of expensive solar absorbers such as photovoltaics.

Furthermore, this would represent a natural extension to BIPVT systems such as that demonstrated by Anderson et al.

[8]. Such systems have been shown to provide an opportunity to improved output from photovoltaic and thermal systems. Therefore in this study a BIPVT concentrator system was developed that incorporated a V-trough concentrator to determine if such a system could produce a worthwhile increase in electrical and thermal energy for a BIPVT style collector.

II. OPTICAL DESIGN OF THE BIPVTC

As noted, [8] had previously demonstrated the use of BIPVT collectors based on trapezoidal profiled long run metal roofs. Therefore it was proposed that this concept be altered to increase the depth of the troughs and to fabricate the system from a mirror-finish stainless steel, where the inclined sides would act as reflective elements directing light onto the photovoltaic absorber, the result being a Building Integrated Photovoltaic Thermal Concentrator (BIPVTC).

It is well known that a flat plate solar collector mounted at an angle close to latitude will give the maximum annual output. Therefore it was decided that, when installed, the photovoltaic absorber in the V-Trough should be inclined to the horizontal at an angle equal to the local latitude (37.5 degrees for Hamilton) with the troughs being oriented East-West. It was suggested that the V-Trough angle (Φ) be set at 25 degrees, to account for the annual variation in declination, with a geometric concentration ratio (aperture area (A) to trough area (a)) of 2.36, as shown in Fig. 1.

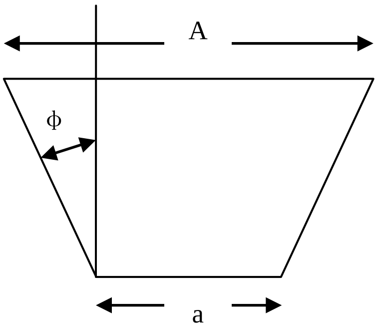

Fig. 1: Schematic of BIPVTC

In order to model the radiation captured by the BIPVTC, Fraidenraich's [9-10] analytical solution for a V-Trough concentrator was used to determine the theoretical optical efficiency, where the total solar reflectance of the polished steel was taken to be ρ = 0.67 [11]. The optical efficiency of the concentrator (η_F) was calculated as a function of incident angle (θ_i), concentration ratio (C), trough half-angle (φ), and material reflectivity (ρ): $\eta_F(\theta_i, C, \varphi, \rho)$.

III. THERMAL DESIGN OF THE BIPVTC

To determine the thermal performance of the BIPVTC a one-dimensional steady state thermal model for an unglazed solar collector was utilised.

Under these conditions the useful heat gain can be calculated using (1).

$$Q_t = AF_R\left[(\tau\alpha).G'' - U_L(T_i - T_a)\right] \qquad (1)$$

Where the useful heat gain (Q_t) can be represented as a function of the collector area (A), the heat removal efficiency factor (F_R), the transmittance-absorptance product of the collector ($\tau\alpha$), the incident radiation (G", which is taken as the product of the concentration and the radiation on a flat inclined surface), the collector heat loss coefficient (U_L) and the temperature difference between the collector inlet temperature (T_i) and the ambient temperature (T_a)

Of these parameters, the transmittance-absorptance product is the only one that is based solely on a physical property of the collector material. The absorptance provides a measure of the proportion of the incoming solar radiation captured by the absorber surface, in this case the photovoltaic cells. The transmittance component measures the portion of the radiation transmitted by any glazing layer and in this case for an unglazed collector it was assumed to be equal to unity. Therefore, to understand the optical characteristics of the building integrated collector it was decided to determine its absorptance characteristics over the Air Mass 1.5 (AM1.5) solar spectrum.

To determine the absorption of the photovoltaic absorber, the diffuse reflectance (ρ) of a small sample was measured at 20nm wavelength intervals between 300nm to 2500nm using a spectrophotometer and a 6° integrating sphere at Industrial Research Limited (Wellington, NZ). Based on the reflectance measurement results shown in Fig. 2, it was possible to determine the absorptance (α) component using (2), as it was assumed that the absorber was an opaque surface with zero transmittance.

$$\alpha = 1 - \rho \qquad (2)$$

By integrating the absorptance derived from the measurements of the reflectance over the range of AM1.5 wavelengths it was found that the photovoltaic absorber had an absorptance value of 0.875.

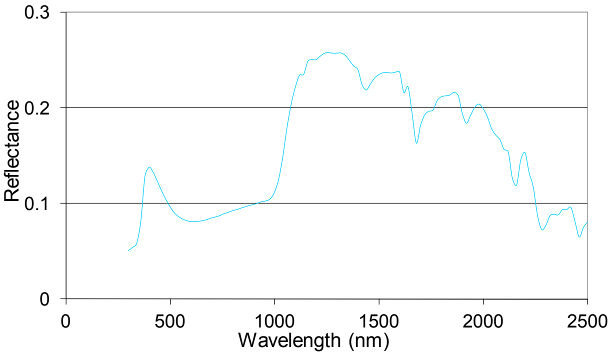

Fig. 2: Reflectance from photovoltaic absorber sample over AM1.5 spectrum

The heat removal efficiency factor (F_R) can be derived from (3), which accounts for the mass flow rate in the collector ($\dot{m}$) and the specific heat of the collector fluid (Cp).

$$F_R = \frac{\dot{m} C_P}{AU_L}\left[1 - e^{-\frac{AU_L F'}{\dot{m} C_P}}\right] \tag{3}$$

To determine the heat removal efficiency factor it is necessary to calculate a value for the corrected fin efficiency (F'). This is done by first calculating the fin efficiency (F) using (4). This determines the efficiency of the finned area between adjacent tubes and takes into account the influence of the tube pitch (W) and the tube width (d). Furthermore, the coefficient (M) accounts for the thermal conductivity and thickness of the photovoltaic absorber and is derived from (5).

$$F = \frac{\tanh\left(M\dfrac{W-d}{2}\right)}{\left(M\dfrac{W-d}{2}\right)} \tag{4}$$

$$M = \sqrt{\frac{U_{loss}}{k_{abs}L_{abs} + k_{PV}L_{PV}}} \tag{5}$$

Therefore, the corrected fin efficiency (F') can be calculated using (6), the overall heat loss coefficient (U_L) of the collector is the summation of the collector's edge (negligible), bottom and top losses. Further, h_{PVA} is a "quasi" heat transfer coefficient to account for the bond resistance between the PV cell and the absorber [12] and h_{fluid} is the forced convection heat transfer coefficient inside the cooling passage determined from the Dittus-Boelter equation.

$$F' = \frac{\dfrac{1}{U_L}}{W\left[\dfrac{1}{U_L(d+(W-d)F)}\right] + \dfrac{1}{Wh_{PVA}} + \dfrac{1}{\pi d h_{fluid}}} \tag{6}$$

For unglazed collectors as used in this study, the top loss coefficient is a function of both radiation and wind. As such it is necessary to calculate the top loss coefficient (U_{top}) by taking the summation of the individual contributions of radiation, natural and forced convection. Under such conditions, the heat loss due to radiation can be expressed as a radiation heat transfer coefficient in terms of the sky temperature (T_s), the mean collector plate temperature (T_{pm}) the plate emissivity (ε_p), and the Stefan-Boltzman constant (σ) as shown in (7).

$$h_r = \sigma\varepsilon_p (T_{pm}^2 + T_s^2)(T_{pm} + T_s) \tag{7}$$

where the sky temperature is represented by the modified Swinbank equation as a function of the ambient temperature as shown in (8) [13].

$$T_s = 0.037536\, T_a^{1.5} + 0.32\, T_a \tag{8}$$

and the mean plate temperature is determined from (9).

$$T_{pm} = T_i + \frac{Q_t / A}{F_R U_L}\left(1 - F_R\right) \tag{9}$$

Furthermore, the losses due to natural and forced convection must also be taken into account. The forced convection heat transfer coefficient (h_w) can be calculated using a correlation in terms of wind velocity (v), as shown in (10) [14], while the natural convection loss (h_{nat}) can be represented by a function of the temperature difference between the mean collector plate temperature (T_{pm}) and the ambient temperature (T_a) as shown in (11) [15].

$$h_w = 2.8 + 3.0v \tag{10}$$

$$h_{nat} = 1.78(T_{pm} - T_a)^{1/3} \tag{11}$$

Using this method it is possible to determine an overall convection heat transfer coefficient (h_c) by combining both forced and natural convection heat transfer as shown in (12).

$$h_c = \sqrt[3]{h_w^3 + h_{nat}^3} \tag{12}$$

Subsequently by taking the summation of the convection and radiation losses, it is possible to determine the overall top loss heat transfer coefficient (U_{top}) for the unglazed collector.

Now, for an unglazed concentrator with no back insulation, it can be assumed that radiation losses between the back surface and the ground are negligible (due to the relatively low emissivity of the stainless steel and also the small temperature differences between the collector and the ground). However, both natural convection and wind losses are significant, and as such, the back loss (U_{back}) can also be represented by (12) [15]. Therefore the overall heat loss coefficient (U_L) for the collector can be determined by taking the sum of the top (U_{top}) and back (U_{back}) losses.

Therefore, combining the modelled value of the concentration ratio with the prediction of solar radiation over the year, and the thermal modelling, it is possible to calculate the heat removed from the solar collector for any time on any day in the year, and thus its temperature.

On the basis of being able to determine the temperature of the BIPVTC, the electrical efficiency can be calculated based on the difference between the mean temperature and the Nominal Operating Cell Temperature (NOCT), which is typically taken as 298K. As such an increase in the mean temperature of the BIPVTC would result in a reduction in the power output.

For this study it was assumed that the cell had an efficiency of 14.5% at NOCT (being within the typical range of 10 to 20%), and that the temperature dependent efficiency could be represented by (13) similar to that used by Bergene and Lovvik [16].

$$\eta = 0.145\,(1 - 0.0041\,(T_{pm} - NOCT)\,) \tag{13}$$

Therefore, the electrical output can be given by (14).

$$Q_e = \eta AG'' \tag{14}$$

Finally by taking the ratio of the energy gain to the total radiation falling on the collector area (*Q/AG"*) we can subsequently determine the overall theoretical efficiency of the collector.

IV. EXPERIMENTAL SETUP

To validate the model, it was decided to fabricate a prototype BIPVTC and examine its performance using an outdoor thermal test, and compare the results to those predicted by the model. As mentioned the collector was fabricated from a mirror finish stainless steel with the aim of providing a long lasting, reflective surface that is also suitable for fluid flow. Therefore a stainless steel sheet was folded to form a V-trough profile with a square fluid channel (20mm x 20mm) in the centre, as shown in Fig. 3.

Photovoltaic modules were bonded into the trough creating a closed channel for fluid flow. The photovoltaic modules comprised 14 polycrystalline cells (156mm x 156mm) laminated onto a 1mm stainless steel sheet using EVA with a Tedlar top sheet with a rated output of 49Wp.

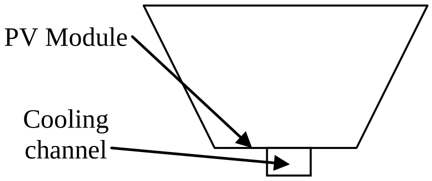

Fig. 3: Cooled BIPVTC Collector

The fluid within the channel serves two purposes; firstly to produce useful thermal energy and secondly to reduce the temperature of the photovoltaic cells, as it is well known that mono-crystalline and polycrystalline silicon PV cells suffer reduced electrical power output at increased temperatures. A flat PV module of the same rated power with no cooling and no concentration was mounted adjacent to the BIPVTC's to act as a reference collector.

To evaluate the BIPVTC performance T-type thermocouples were used to measure the inlet (T_i) and outlet (T_{out}) temperatures of the panels as well as their surface temperatures. The flow rate through the collector was measured using a paddle wheel flow sensor and the incident solar radiation (G") was measured using a pyranometer mounted parallel to the panels. Additionally, ambient temperature (T_a) and wind speed (v) were measured using a nearby weather station.

To determine the electrical output of the modules, the data acquisition system switched between measuring the open circuit voltage (V_{oc}) across the panel and the short circuit current (I_{sc}) of each panel at 15-second intervals. From this it was possible to determine the output power of the collectors from (15).

$$Q_e = FFV_{oc}I_{sc} \tag{15}$$

where I_{sc} is the short circuit current, V_{oc} is the open circuit voltage and FF is the fill factor, given by the PV cell manufacturer to be 0.72.

V. RESULTS

Having developed a mathematical description of the concentration ratio, it was decided to test this against the experimental output from a clear winter's day. For the test day, the optical model suggested that the concentration ratio of the collector would vary, as shown in Fig. 4.

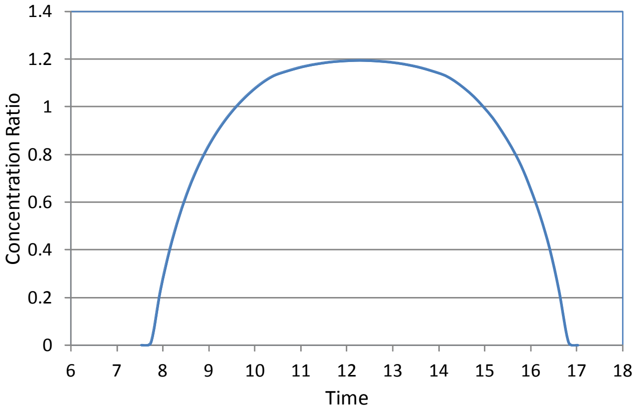

Fig. 4: Modelled concentration ratio for a winter's day

From Fig. 4 it can be seen that the geometry of the V-trough results in shading of the absorber, in the early morning and afternoon. This is manifested as a concentration ratio of less than one, i.e. the radiation at the absorber would be less than if the collector was a flat plate. However, during the middle of the day, there is a higher ratio.

To verify this, the experimental concentration ratio, taken as the ratio of the output from a concentrated collector to that of the control module, was determined. In Fig. 5, it can be seen that there is good correspondence between the optical model and the experimentally derived value.

Therefore it was decided to determine if the electrical output power could also be predicted by the combined optical, thermal, electrical model. In Fig. 6 it can be seen that the model provides a good prediction of the electrical output of the BIPVTC. Further Fig. 6 shows that without cooling, there would be a decrease in the electrical output from the panels.

The decrease in output is manifested principally in the form of a reduced voltage output from the collector. Coventry [6] suggested that increasing photovoltaic cell temperatures leads to a reduced voltage of approximately 1.9mV/°C. In Fig. 7, it can be seen that the model predicts the decrease in output as the temperature of the BIPVTC increases reasonably well.

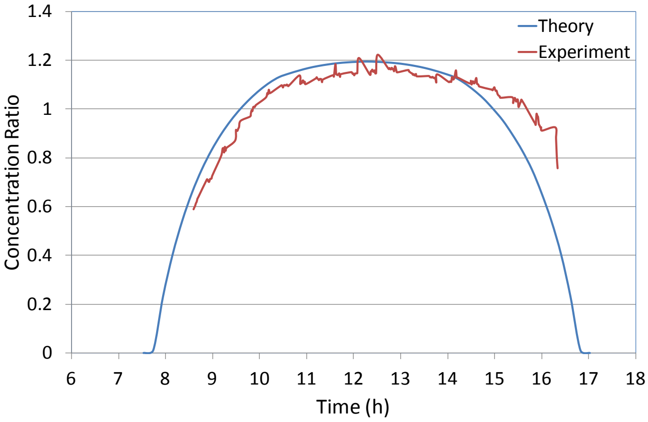

Fig. 5: Validation of optical model

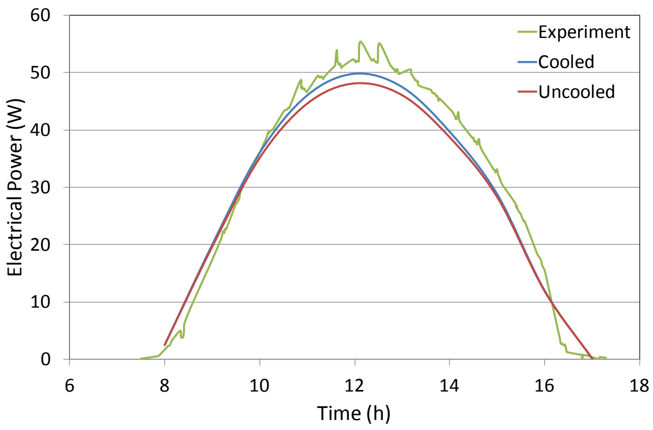

Fig. 6: Experimental and modelled electrical output from BIPVTC

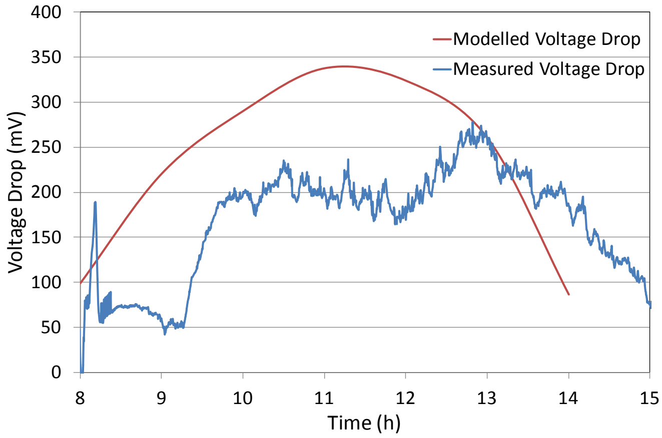

Fig. 7: Experimental and modelled voltage drop in BIPVTC output

The reason for the discrepancy in the modelled and actual voltage drop is best attributed to a difference in the predicted and actual cell temperature. In Fig. 8, it can be seen that there is a corresponding divergence between the modelled and theoretical thermal output. The reason for this may be the result of the limitations of the wind heat loss correlation as well as the sky temperature correlation. However the prediction is generally quite good.

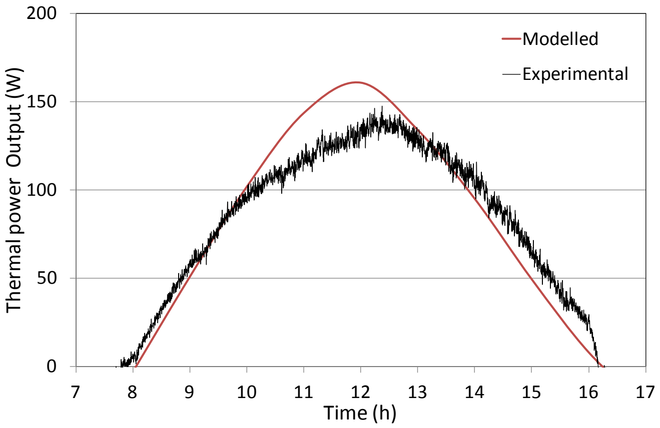

Fig. 8: Experimental and modelled thermal output from BIPVTC

Similarly, in Fig. 9, the prediction of the overall power output (thermal plus electrical) from the collector is also influenced by the variation in the temperature prediction.

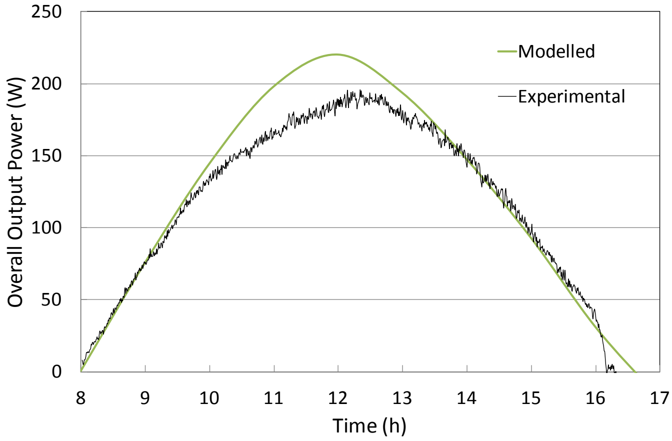

Fig. 9: Experimental and modelled power output from BIPVTC

However, when considering the overall efficiency of the collector, it can be seen in Fig. 10 that the model provides a relatively good prediction of the BIPVTC performance.

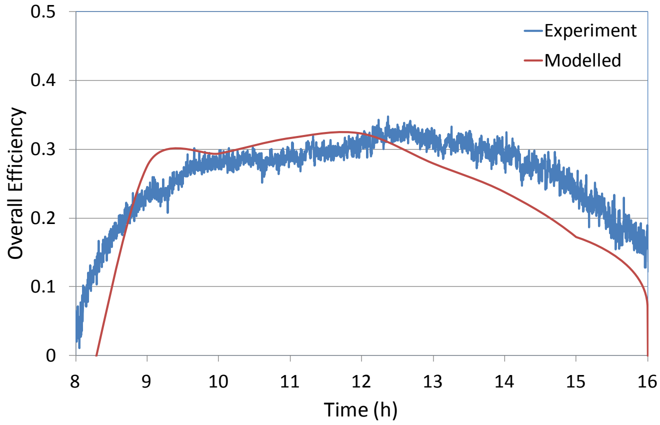

Fig. 10: Experimental and modelled efficiency of BIPVTC

VI. DICUSSION AND CONCLUSION

From the validated modelling, it can be seen that the concept of a building integrated photovoltaic thermal concentrator is feasible and has the potential to increase energy output from photovoltaic modules. Though it could be argued that photovoltaic systems are reducing in price, they are still relatively expensive, and as such the use of low cost reflective elements offers the opportunity to improve electrical energy yields with lower capital outlays.

Moreover, the cooling of the cells in addition to improving the electrical output offers a thermal energy source and hence energy capture for the total area is markedly improved.

As such the combined optical, thermal electrical model could be used to achieve further improvements from the BIPVTC. However there is a need to closer examine the convective and radiative heat losses using improved heat transfer correlations to ensure even better correlation between the theoretical and experimental performance of the collector.

ACKNOWLEDGEMENT

The authors would like to thank Mr Josh Garrett for his assistance in undertaking some of the experimental work.

REFERENCES

[1] W. G. J., van Helden, R. J. C. Van Zolingen, and H. A. Zondag, “PV thermal systems: PV panels supplying renewable electricity and heat”, Progress in Photovoltaics: Research and Applications, vol. 12, pp. 415-442, 2004

[2] Y., Tripanagnostopoulos, T.Nousia, , M. Souliotis, & P. Yianoulis, “Hybrid photovoltaic/thermal solar systems”, Solar Energy, vol. 72 (3), pp. 217–234, 2002

[3] B. J., Huang, T. H Lin, W. C., Hung, and F. S., Sun, “Performance evaluation of solar photovoltaic/thermal systems”, Solar Energy, vol. 70 (5), pp. 443-448, 2001

[4] H.P. Garg, and R.S Adhikari, “Performance analysis of a hybrid photovoltaic/thermal (PV/T) collector with integrated CPC troughs”, International Journal of Energy Research, vol. 23, (15), pp. 1295-1304, 1999

[5] J.I., Rosell, X., Vallverdu, M.A Lechon, and M, Ibanez, “Design and simulationof a low concentrating photovoltaic/thermal system”, Energy Conversion and Management, vol. 46 (18-19), pp. 3034-3046, 2005

[6] J. S. Coventry, “Performance of a concentrating photovoltaic/thermal solar collector”, Solar Energy, vol. 78, pp. 211 – 222, 2005

[7] R.B. Bannerot, and J.R., Howell, “Predicted daily and yearly average radiative performance of optimal trapezoidal groove solar energy collectors”, Solar Energy, vol. 22 (3), pp. 229-234, 1979

[8] T. N Anderson, M. Duke, G. L. Morrison, and J. K. Carson, “Performance of abuilding integrated photovoltaic/thermal (BIPVT) solar collector”, Solar Energy, vol. 83, pp. 445– 455, 2009

[9] N. Fraidenraich, “ Analytic solutions for the optical properties of V-troughconcentrators”, Applied Optics, vol. 31 (1), pp. 131 – 139, 1992

[10] N. Fraidenraich, “Design procedure of V-trough cavities for photovoltaicsystems”, Progress in Photovoltaics: Research and Applications, vol. 6 (1), pp. 43-54, 1998

[11] B. Karlsson, and C. G Ribbing, “Optical constants and spectral selectivity of stainless steel and its oxides”, Journal of Applied Physics, vol. 53 (9),pp. 6340-6346, 1982

[12] H.A., Zondag, D.W., de Vries, W.G.J., van Helden, R.J.C., van Zolingen, and A.A. van Steenhoven, “The thermal and electrical yield of a PV-thermal collector”, Solar Energy, vol. 72, (2), pp.113-128, 2002

[13] M.K., Fuentes, 1987, “A simplified thermal model for flat-plate photovoltaic arrays”, Sandia National Laboratories Report, SAND85-0330-UC-63, Albuquerque

[14] J.H. Watmuff, W.W.S Charters, and D. Proctor, D, “Solar and wind induced external coefficients for solar collectors”, Comples No. 2, 56, 1977

[15] U. Eicker, “Solar technologies for buildings”, John Wiley and Sons, Chichester, 2003

[16] T. Bergene, and O.M. Lovvik, “Model calculations on a flat-plate solar heat collector with integrated solar cells”, Solar Energy, vol 55, (6), pp. 453-462, 1995