Chapter 8

Conclusions and Recommendation for Further Work

8.1 Conclusions

8.1.1 Theoretical Investigation

Detailed optical, heat transfer and electrical simulations of the asymmetric compound parabolic photovoltaic concentrators were undertaken.

8.1.1.1 Optical Simulations

A two dimensional ray trace technique was used to investigate the effects of angular acceptance functions and optical efficiencies. Optical analysis showed that the;

- ACPPVC-50 system achieved optical efficiencies of up to 85.15% for a wide range of incident solar radiation angles
- ACPPVC-50 system has 100% collection efficiencies for incident solar radiation within the angles of 38° to 89° (to the vertical)
- number of reflections occurring at reflector surfaces is the main source of optical losses.

8.1.1.2 Heat Transfer Simulations

A finite element based model was used to predict the operating solar cell temperature with realistic boundary conditions applied in the model. Conduction in the aperture cover, reflector substrate, solar cell and aluminium back plate were modelled along with convection in the different regions. The following configurations have been simulated

- a single trough ACPPVC-50 for a range of incident solar radiation intensities at the aperture cover
- a three trough ACPPVC-50 for a incident solar radiation intensity of 1000 Wm^{-2} at the aperture cover
- a five trough ACPPVC-50 for
    - a range of incident solar radiation intensities at the aperture cover
    - 10, 20 and 30-mm air gaps adjacent to the aperture cover with inlet air velocities of 0.2 ms^{-1}, 0.4 ms^{-1}, 0.6 ms^{-1}, 0.8 ms^{-1} and 1.0 ms^{-1} and with natural convection inside the cavity
    - 10 and 20-mm air gaps adjacent to the aluminium back plate and adjacent to the aperture cover with inlet air velocities of 0.1 ms^{-1}, 0.5 ms^{-1} and 1.0 ms^{-1}.

The heat transfer analysis showed that

- the maximum solar cell surface temperature for a single trough ACPPVC-50 is nearly 20°C lower than for the five trough ACPPVC-50 due to differences in heat loss areas between both configurations

- the isotherms are taller and thinner for higher solar radiation intensities due to the larger temperature difference between the aperture cover and the solar cell surface
- an inlet air velocity of 1.0 ms^{-1} decreased solar cell surface temperature by up to 22°C for a front air channel of width 20 mm adjacent to the aperture cover
- a maximum temperature reduction of 33°C occurred for an inlet air velocity of 1 ms^{-1} at the front and rear air channels of width 20 mm.

8.1.1.3 Electrical Simulations

The following conclusions have been drawn from the electrical simulations:

- a temperature coefficient of open circuit voltage of 0.24 $V°C^{-1}$ occurred for every degree of temperature rise of the solar cell surface
- the maximum power point decreased by 0.45% for ever 1°C increase of solar cell surface temperature.

8.1.2 Experimental Investigation

Indoor experimental characterisation under an in-house developed continuous solar simulator and outdoor experimental investigations were undertaken for two systems, an ACPPVC-50 system and a non-concentrating system with different numbers of PV string combinations.

8.1.2.1 Indoor Experimental Investigation Using a Continuous Solar Simulator

Four different PV panels were constructed and exposed to more than 10 hours of continuous solar simulation to investigate the effect of temperature on the I-V characteristics. A 10° inclination angle for the ACPPVC-50 system increased the maximum power point by approximately 70% compared to a 0° inclined ACPPVC-50 system. Indoor experimental characterization showed an efficiency improvement of 8.3% for the air filled ACPPVC-50 compared to a non-concentrating PV panel.

8.1.2.2 Outdoor Experimental Investigations

Two ACPPVC-50 systems of dimension 1.11m × 0.615m were constructed and commissioned on the 20th August 2002. The following experiments were conducted:

- System 1 (the ACPPVC-50 system made initially with a replaced solar cell) was monitored with and without concentrator elements
- A non-concentrating flat and ACPPVC-50 system were monitored simultaneously.

The maximum power point increased for the System 1 by 1.62 compared to the same system without concentrators although the design concentration ratio of the system was 2.01. The concentrator back plate temperature rise was only 12°C higher compared to the flat non-concentrating system.

During the simultaneous experimental investigation of the non-concentrating and concentrating systems, the maximum power point was 1.65 times greater for the concentrating system as shown in figure 8.2.2.1. From the different series combination of the PV strings better performance can be seen for fewer strings connected in series. There is the result of the shading effect caused by the wooden frame and electrical losses between the solar cells, the maximum power ratio can nevertheless be improved by up to 1.9 by reducing the tab spacing, this is verified experimentally in section 7.4.1. The highest electrical efficiency achieved by a single PV string was 12% for the non-concentrating system compared to 10.5% for the concentrator, from this it is deduced that a significant resistive loss occurs between interconnected solar cells. The electrical efficiency of the non-concentrating system was 8% whereas the electrical efficiency of ACPPVC-50 was 6.8% for most series configurations. An average of 6-8% maximum power difference occurs when comparing the performance of systems with a 52 mm long tab space and 2-mm long tab space between solar cells for a string of 5 solar cells connected in series. The modified maximum power curve and variation in efficiency with incident solar radiation for non-concentrating and the ACPPVC-50 systems are shown in figure 8.2.2.2 and figure 8.2.2.3 respectively, when four PV strings were connected in series.

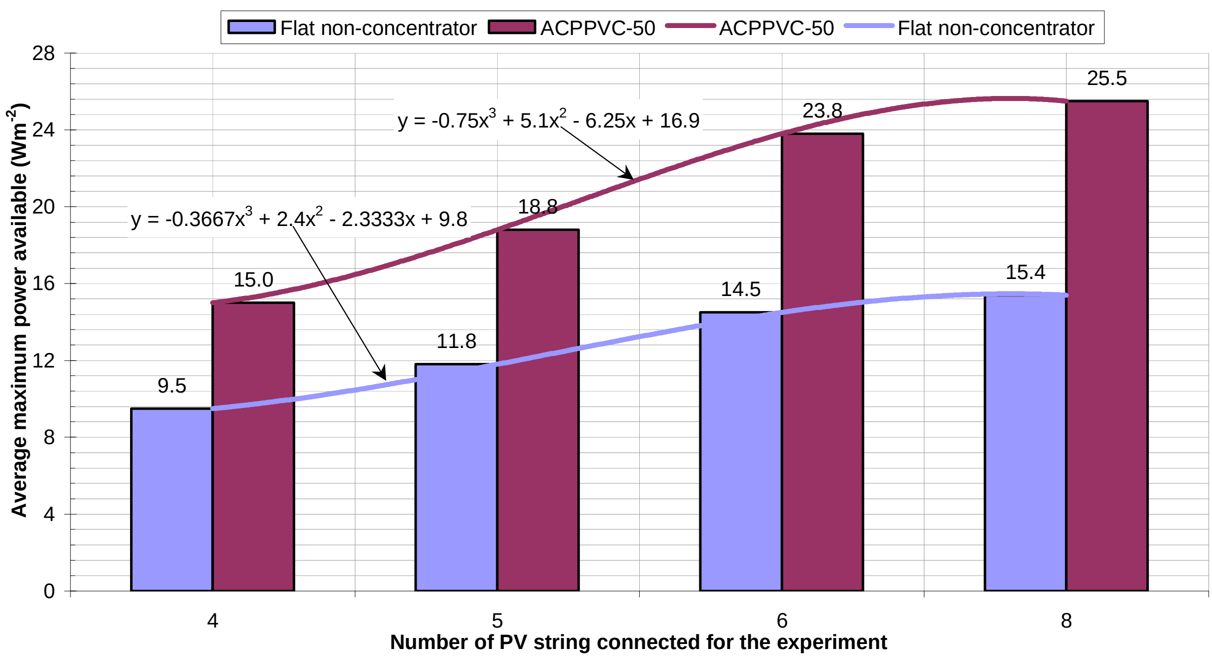

Figure 8.2.2.1 Maximum power available for different series combinations of PV strings for the non-concentrating and the ACPPVC-50 system. The calculation was made based on the data points available as described in chapter 6, the maximum power available was calculated on the basis of 1000 Wm^{-2} incident solar radiation.

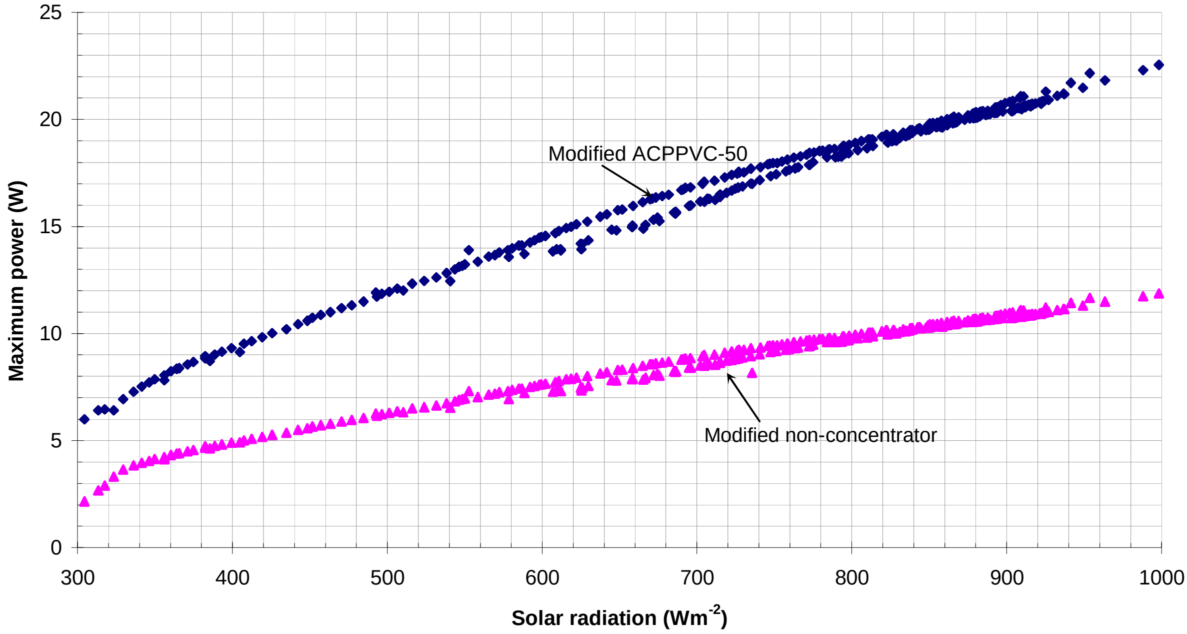

Figure 8.2.2.2 Maximum power of the non-concentrating and the ACPPVC-50 systems when four PV strings were connected in series. The calculation was made based on figure 6.4.7.5 (page 219) assuming a power ratio of 1.9.

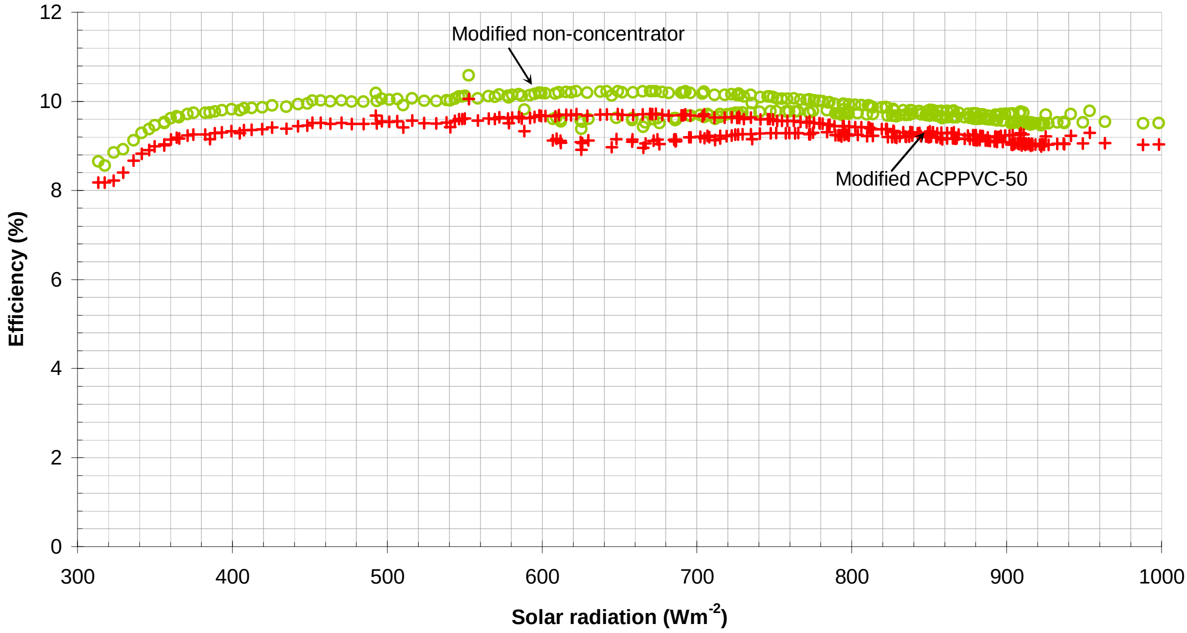

Figure 8.2.2.3 Efficiency of the non-concentrating and ACPPVC-50 systems when four PV strings were connected in series. The calculations were made based on figure 6.4.7.7 assuming a power ratio of 1.9.

The equation 1.7.4.1 (page 40) does not incorporate optical losses in the system. Incorporating the optical efficiency of the PV system equation 1.7.4.1 becomes

$$T_{pv} = (1-\eta_{elec}\eta_{op})\times(I_g)\times R_{th} \tag{8.2.2.2}$$

where η_{elec} and η_{op} are the electrical efficiency and optical efficiency of the photovoltaic system. The thermal resistance R_{th} was calculated for the non-concentrating and the concentrating systems using equation (8.2.2.1). These results are compared with values reported previously in the literature and are shown in figure 8.2.2.4. Incorporating optical losses with an optical efficiency of 85.5% (as detailed in chapter 3), the thermal resistance are:

$$R_{th,flat} = 0.0505 \quad for \quad the \quad non-concentrating \quad system$$

$$R_{th,con} = 0.0627 \quad for \quad the \quad ACPPVC\text{-}50 \quad system$$

The experimental results and the simulation are in good agreement when comparison is made between temperature measurements at the aluminium back plate, reflector substrate and inside glass cover temperatures with those predicted. Both electrical and thermal predictions vary between +3.8% to -5.8% for a heat loss coefficient of 13.5 $Wm^{-2}K^{-1}$ when compared to experimental measurements as shown in table 7.5.1.

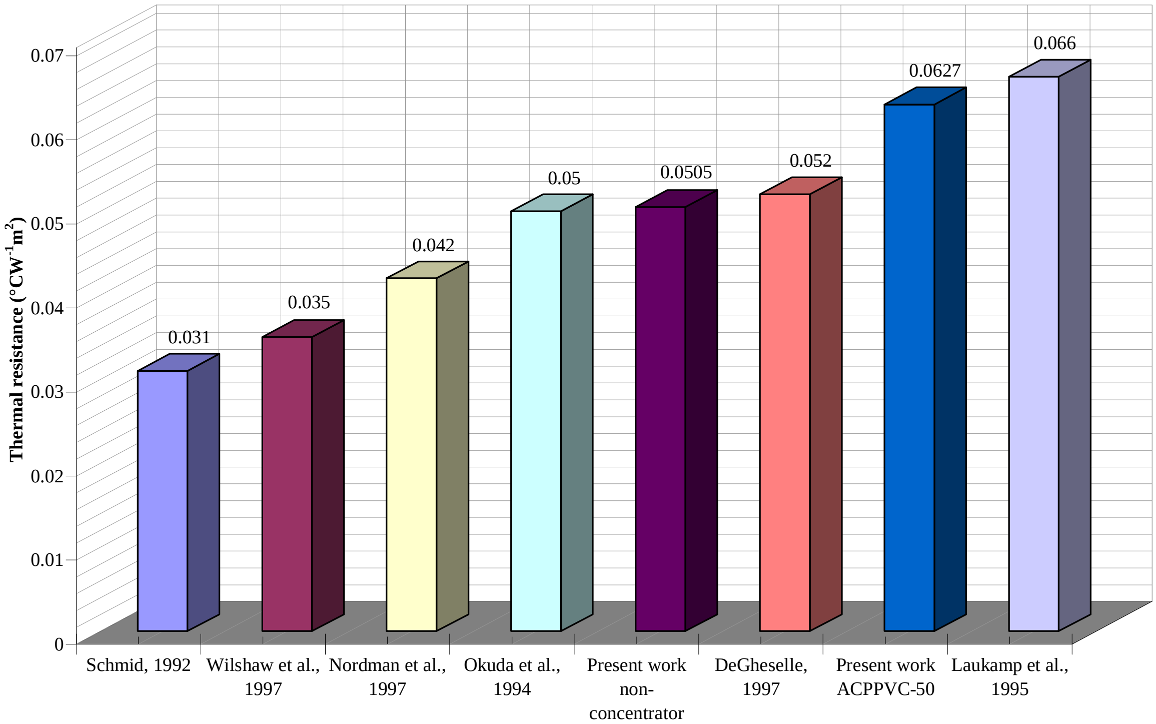

Figure 8.2.2.4 Value of thermal resistances from previous and present study. Previous studies are shown in table 1.7.4.1 (page 40). The value in the present study was calculated using the equation 1.7.4.1. For the present study the efficiency and average solar cell temperatures were extracted from figure 6.4.9.4 (page 229) and figure 6.4.9.5 (page 230) respectively.

8.2 Recommendations for Future Work

Air filled asymmetric compound parabolic photovoltaic concentrators have been proven to have superior collection performance compared to similar non-concentrating systems delivering more power per unit PV area. However to optimise the present system to enable use as a building integrated PV façade element further research is required as follows:

- A three-dimensional model is required for both the optics and heat transfer that occurs in an ACPPVC-50 system.
- Phase change materials along with metal fins can be incorporated at the aluminium back plate to reduce solar cell operating temperature.
- Spectrally selective optical coatings could be developed to reduce non-useful energy entering the system through the aperture cover.
- Solar cells with short tab spacing would reduce resistive power loss, this would require design of an optimised ACPPVC-50 system.
- The optical design of the ACPPVC-50 system can be applied to medium and high temperature solar water heating applications.
- Long term monitoring is required to assess the ACPPVC-50 system for durability and performance prior to integration into the building façade. This would provide long term performance data on any thermal and chemical effects on system components that would determine durability to weather conditions.
- Modular designs need to be produced to enable ease of installation.
- Research is required into mass manufacturing processes to achieve a viable market cost.

The above recommended research would produce findings which would enhance the overall efficiencies of concentrating solar energy systems for both photovoltaic and solar thermal applications. This research would reduce the cost per unit energy generated for photovoltaic systems integrated into the building façade.