Thermal and electrical performance of a concentrating PV/Thermal collector: results from the ANU CHAPS collector

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Abstract
The combined heat and power solar (CHAPS) collector under development at the ANU is a PV/Thermal collector utilizing parabolic mirrors to concentrate light by a factor of 25-35x. This paper presents some measured results for thermal and electrical output from the CHAPS collector, as well as an overview of the major components of the CHAPS collector.

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 first CHAPS prototype is a 25x concentration domestic style system, suitable for hot water and electricity generation for a home. Recently a second CHAPS system prototype has been developed, a 35x concentration single-axis tracking system, designed for installation on the roofs of commercial and light industrial buildings, to contribute to building heating, cooling and power requirements. The development of the CHAPS systems was preceded by PV trough technology development at the ANU since the mid-1990s, culminating in the commissioning of a 20kW PV trough array at Rockingham, Western Australia, in 2000.

2 Current development

2.1 Domestic CHAPS

The domestic CHAPS system (figure 1a) is a two-axis tracking system made up of two individual mirrors, each 1.6m long and 1.2m wide, spaced 0.2m apart. Light is focused onto a 40mm wide strip of monocrystalline silicon solar cells of around 20% absolute efficiency. The cells are adhered to an aluminium cell tray, which is bonded to a copper pipe. Water is passed through the pipe to cool the cells and collect thermal energy, which is then stored in a Solahart Streamline solar hot water tank. The cells are connected to each other in series, with bypass diodes across groups of cells. The first prototype differs from later prototypes in two key areas; the mirror is a laminated glass formed mirror rather than a glass-on-metal laminate (GOML) mirror, and the water is carried by an aluminium channel bonded to the cell tray rather than a copper pipe. The second and third CHAPS prototypes have been constructed and installed, and a further 30 systems are planned during the coming 12 months for house roofs in the Canberra region as part of a broader trial supported by the Sustainable Energy Development Authority of NSW.
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2.2 Long CHAPS

The Long CHAPS system (figure 1b) is a single-axis tracking version of the domestic CHAPS system. The first prototype system consists of 10 mirrors, each 1.6m wide and 1.5m long, forming a 15m long parabolic trough. The major components such as receivers, mirrors and solar cells are essentially the same as for the domestic system. The prototype Long CHAPS system is partially constructed, and will form the basis of testing prior to the installation of a 350m² system at Bruce Hall (a residential college at the ANU) at the end of this year. This system, supported by Bruce, Burton & Garran, the Australian Greenhouse Office and Solahart, will provide heating hot water and domestic hot water for two buildings, and will be the largest installation of combined PV/thermal parabolic trough collectors to date.

3 Major CHAPS components

3.1 GOML Mirrors

The CHAPS collectors use parabolic curved mirrored troughs that focus light onto a strip of solar cells. The mirrors were developed at the ANU by Glen Johnston and Greg Burgess, and follow on from similar development of three-dimensional curved mirrors for dishes (Johnston et al, 2001). The glass-on-metal laminate (GOML) mirrors are composed of a silver backed mirror 1mm thick, laminated with EVA to a sheet of 0.8mm thick ‘Colorbond’ sheet metal. The GOML mirrors have accuracy around 90%, which describes the percentage of reflected light that is incident on the solar cells along the length of the trough. The mirrors are around 91% reflective, which compares well with other reflective surfaces such as anodised aluminium at 81% (Brogren et al., 2000). While the overall concentration ratio is around 30x, the illumination flux intensity is far from even across the width of the solar cell, as shown in figure 2. Flux density peaks at upward of 100 suns in the centre of the cell.

Figure 2. Flux density of light at the focus of a GOML mirror for a slice at the centre of the mirror, based on results from photogrammetry by Glen Johnston and Greg Burgess.
3.2 Silicon Solar Cells

Monocrystalline silicon solar cells are produced at the ANU especially for concentrator systems such as the CHAPS system. The cells are designed to have low internal series resistance, since the high current density at light concentration of around 30x significantly affects the fill factor of the cell. Shunt resistance losses are usually negligible at high concentration ratios. Using typical values for a good solar cell, the IV curves for a range of series resistances have been plotted in figure 3. The graph shows clearly that a one-sun solar cell, designed with a series resistance around 0.5 _cm², has a terrible fill factor when illuminated to 30 suns. This can be compared to a typical ANU concentrator cell, with series resistance of 0.043 _cm².

Low series resistance is achieved in the ANU concentrator cells by a) narrow spacing of the conductive fingers, which reduces the distance electrons travel through the silicon, b) heavy phosphorous doping beneath the fingers to reduce the contact resistance and c) and relatively large electroplated silver finger cross-section.

![Graph](image1)

**Figure 3a. I-V curves for a solar cell under 1 sun illumination for a range of values of series resistance**

*Other values used in the equivalent circuit equation:*

- $R_{sh} = 1000 _cm²$
- $J_0 = 10^{-13} A/cm²$
- $kT/q = 25.7 mV$

- $J_L = 38 mA/cm²$
- $R_L$ units are _cm²

3.3 Receivers

The CHAPS receivers are made up of solar cells mounted on an aluminium extrusion bonded to a copper pipe containing the heat transfer fluid.

![Diagram](image2)

**Figure 4. Cross-section of a CHAPS receiver.**

In order to maintain electrical efficiency, it is important to minimise the temperature difference between the fluid and the solar cells. Therefore, very good heat transfer is required between the silicon and the water, particularly due to the high heat flux generated at the centre of the cell. Silicon, aluminium and copper are all very good thermal conductors. Most thermal resistance comes from the bonds between these materials, in particular between the silicon and aluminium.
4 Measured thermal performance

The CHAPS system being monitored is the first CHAPS prototype, installed on the roof of the Faculties Teaching Centre at the ANU, with dimensions as stated in Section 2.1. The location of the system has latitude of 35.3°S, and is mounted on a roof tilted at 19.2° that faces 36.0°E. Figure 5 shows the measured thermal output for the unshaded receiver on 16 August 2001, as well as inlet and outlet temperatures for both receivers, weather data and limited electrical performance data.

Some observations from this data are:
- There is a gradual rise of inlet temperature throughout the day as the thermal storage tank heats up.
- There is a gradual fall in thermal efficiency throughout the day, from about 50% to 40% as the tank heats up. Thermal efficiency is calculated by dividing the thermal output by the product of direct beam irradiation and mirror aperture.
- Open circuit voltage falls gradually throughout the day for both receivers as the cooling water heats up.
- The short circuit current of the shaded receiver 1 drops significantly in the afternoon and early morning when compared to the unshaded receiver 2.
- The wind becomes stronger in the afternoon and ambient temperature peaks at around 2pm.
- The temperature at the outlet to the shaded receiver $T_{\text{middle}}$ approaches the temperature at the inlet $T_{\text{in}}$ during the late afternoon.
- There is shading of the entire system early in the day and late in the day, as both direct radiation and total horizontal radiation dip.
- There is a tracking problem in the middle of the day, as direct radiation dips while total horizontal radiation remains unaffected.

![Figure 5. Measured data from the CHAPS system on 16 August 2001.](image)

The equations describing the heat transfer for a concentrating PV/T collector is developed in Coventry (2002). Based on these equations, we would expect a fall in thermal efficiency during the afternoon, as the increase in operating temperature causes higher convective and radiative losses, and the increase in wind speed also increases the convection coefficient. The shading factor is a calculated quantity that describes how much shade the forward mirror casts on the...
rear mirror, and explains why the shaded receiver is affected more significantly in the afternoon than in the morning. In mid-August, shading begins around 1pm due to the orientation of the roof. Unfortunately electrical data at the maximum power point was not available for this period due to some problems with the MPP tracker. However, the solar cells have been under load with a fixed resistor keeping the output close to maximum power and therefore the thermal energy output is additional to electrical energy output, which could be expected to be between 10-11% efficient based on the Voc and Isc measurements. The open circuit voltage falls throughout the day because of the increase in cell temperature. The short circuit current is proportional to the illumination, and therefore is significantly affected by the shading.

5 Electrical performance

While the simple assumptions made about electrical performance outlined in Coventry (2002) are adequate for the thermal model, in reality the electrical performance of the receiver is much more complex. The impact of tracking errors, shading, diode placement, mirror imperfections, non-uniform illumination and temperature, and variations between cells make it difficult to achieve anything near the efficiencies apparent when individual cells are tested in laboratory conditions. The model also neglects the temperature and illumination gradients perpendicular to the flow. However in reality, they change significantly across the width of the receiver. To explore the temperature distribution perpendicular to the flow, a finite element model was set up using the software package Strand7. Figure 6 shows the temperature distribution of a CHAPS style receiver under typical operating conditions with a light breeze, turbulent fluid flow and a water temperature of 55°C.

![Figure 6. Temperature distribution within the receiver as modeled using Strand7.](image)

A temperature profile through the middle of the solar cell is taken from the model, and plotted in figure 7. The graph shows a temperature difference of up to 14°C between the middle of the cell and the edges. Therefore, the centre of the cell, where most current is generated, operates at a higher temperature than the average cell temperature, and the total electrical output will be less than predicted by simple models. Improvement of the heat transfer between the solar cells and the absorber by an order of magnitude would reduce the temperature difference between the center of the cells and the receiver by around 10°C. While highly thermally conductive but electrically insulating materials are available (such as alumina), they are costly and the additional electricity generated does not justify the cost for a medium concentration system.

![Figure 7. Temperature distribution across the solar cell](image)
The overall dependence of efficiency on temperature for a receiver on sun has been experimentally determined to be around 0.41%/°C relative, based on analysis of IV curves such as those shown in figure 8. The impact of non-uniformities in the flux distribution of light can be seen in the kinks in the curve, which correspond to bypass diodes switching on, and have the effect of reducing the fill factor to around 0.63. Electrical efficiency at a typical operating temperature of 65°C is around 10.5% absolute, based on the projected mirror area including shading by the receiver.

![IV curves for various temperatures for a receiver on the demo trough.](image)

Figure 8. IV curves for various temperatures for a receiver on the demo trough.

6 Conclusion

Early results from the first CHAPS collector indicate thermal efficiencies around 50% and electrical efficiencies upward of 10% are achievable throughout the sunlight hours of the day. It is expected that recent developments in the design of the receivers and mirrors since the first prototype will further improve both thermal and electrical efficiency. However, experimental results from these systems are not yet available.

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8 References

