A solar concentrating photovoltaic / thermal collector

Joseph Sydney Coventry
June 2004
Declaration

This PhD thesis contains no material that has been accepted for the award of any other degree or diploma in any university. To the best of the author’s knowledge and belief, no material previously published or written by another person has been included in this thesis, except where due reference is made in the text.

Joe Coventry
June 2004
Acknowledgements

This thesis would not have been possible without the generous academic support of my two supervisors, Andrew Blakers and Keith Lovegrove. They have given me solid guidance throughout the PhD, and their optimism and commitment towards the cause of renewable energy is certainly inspirational. Many thanks also to Chris Bales in Sweden for his help as an advisor, and for bringing me up to speed with TRNSYS during his year at the ANU.

I would like to acknowledge the generosity and patience shown by the administration at the Centre for Sustainable Energy Systems and the Faculty of Engineering and Information Technology during the last four years. I have had the opportunity to conduct an international study tour, attend local and international conferences, and to take some time out while working on the Bruce Hall solar project. Both CSES and FEIT have been generous with financial support and encouraged extra-curricular developmental activities. Thanks also to the now defunct CRC for Renewable Energy for their funding support and good fun post-graduate conferences.

To my fellow CHAPS team, it has been a pleasure to work with you, up on the roof, in the labs and sitting around the table discussing ideas. A few people deserve special mention: James Cotsell for his enthusiasm and willingness to get things done, and especially for accelerating the construction of the long trough; Bruce Condon, for advice on all things measurement and electrical; John Smeltink, for regularly getting his hands dirty to ‘get the job done’; Greg Burgess, for his help on cold winter nights with the photogrammetry; Will Keogh, for advice with LabView and the flash tester; and the team of people who have helped out in the workshop, particularly Luke Clayton, Jeff Brown, Tony Ashmore, Ben Nash and Jaap den Hartog.

My office mates have been absolutely fantastic. Holger Kreetz was a real motivator, not just on the soccer field, but in discussions on thermodynamics and the thesis in general during the early days. Thanks to Mike Dennis for teaching me about wires and sharing the frustrations of TRNSYS, and Evan Franklin for a shot and a half of coffee, Monday footy analysis and help with the flux measurements (in no particular order). Thank you also Dave, Liz, Paul and Tom for helping make the office such a great work environment, and top notch place to hang out!

Thank you friends and family for your support. Most of all, thank you Leonie for moving up to Canberra, marrying me and making life outside the thesis good.
Abstract

This thesis discusses aspects of a novel solar concentrating photovoltaic / thermal (PV/T) collector that has been designed to produce both electricity and hot water. The motivation for the development of the Combined Heat and Power Solar (CHAPS) collector is twofold: in the short term, to produce photovoltaic power and solar hot water at a cost which is competitive with other renewable energy technologies, and in the longer term, at a cost which is lower than possible with current technologies. To the author’s knowledge, the CHAPS collector is the first PV/T system using a reflective linear concentrator with a concentration ratio in the range 20-40x. The work contained in this thesis is a thorough study of all facets of the CHAPS collector, through a combination of theoretical and experimental investigation.

A theoretical discussion of the concept of ‘energy value’ is presented, with the aim of developing methodologies that could be used in optimisation studies to compare the value of electrical and thermal energy. Three approaches are discussed; thermodynamic methods, using second law concepts of energy usefulness; economic valuation of the hot water and electricity through levelised energy costs; and environmental valuation, based on the greenhouse gas emissions associated with the generation of hot water and electricity. It is proposed that the value of electrical energy and thermal energy is best compared using a simple ratio.

Experimental measurement of the thermal and electrical efficiency of a CHAPS receiver was carried out for a range of operating temperatures and fluid flow rates. The effectiveness of internal fins incorporated to augment heat transfer was examined. The glass surface temperature was measured using an infrared camera, to assist in the calculation of thermal losses, and to help determine the extent of radiation absorbed in the cover materials. FEA analysis, using the software package Strand7, examines the conductive heat transfer within the receiver body to obtain a temperature profile under operating conditions.

Electrical efficiency is not only affected by temperature, but by non-uniformities in the radiation flux profile. Highly non-uniform illumination across the cells was found to reduce the efficiency by about 10% relative. The radiation flux profile longitudinal to the receivers was measured by a custom-built flux scanning device. The results show significant fluctuations in the flux profile and, at worst, the minimum flux intensity is as much as 27% lower than the median. A single cell with low flux intensity limits the current and performance of all cells in series, causing a significant drop in overall output. Therefore, a detailed understanding of the causes of flux non-uniformities is essential for the design of a single-axis tracking PV trough concentrator. Simulation of the flux profile was carried out
using the ray tracing software Opticad, and good agreement was achieved between the simulated and measured results. The ray tracing allows the effect of the receiver supports, the gap between mirrors and the mirror shape imperfections to be examined individually.

A detailed analytical model simulating the CHAPS collector was developed in the TRNSYS simulation environment. The accuracy of the new component was tested against measured data, with acceptable results. A system model was created to demonstrate how sub-components of the collector, such as the insulation thickness and the conductivity of the tape bonding the cells to the receiver, can be examined as part of a long term simulation.
Foreword

The author would like to acknowledge colleagues at CSES for their contributions to the design and production of the CHAPS system. The receiver design was modified from the air cooled system used for the Rockingham PV trough project, which is a two-axis tracking PV concentrator system designed by the ANU (Smeltink et al., 2000). The author was responsible for many of the key changes to this design, in particular, the shift to a full aluminium extrusion (with the use of anti-corrosive additives in the cooling fluid) and the inclusion of internal fins to improve the heat transfer. The design team, led by James Cotsell, assisted with realising the design and fabricating the receivers. The author was also responsible for the system design change from two-axis tracking CHAPS systems to single-axis tracking long troughs. The detailed mechanical drawings for the single axis tracking system were coordinated by John Smeltink, and the manufacturing was outsourced. The mirrors were designed by Glen Johnston and Greg Burgess, and manufactured in the solar thermal workshop at the ANU. The monocrystalline silicon solar cells were manufactured in the photovoltaic laboratory at the ANU, by a dedicated and persistent team lead by Chris Holly. The solar tracking controller was developed and built by Mike Dennis. The author carried out the experimental work to examine the impact of non-uniform light across solar cells, but would like to acknowledge the work of Evan Franklin in developing a theoretical model to further explain the results. The author would like to acknowledge the contribution by Keith Lovegrove to chapter 3, which is largely taken from a co-authored journal paper (Coventry and Lovegrove, 2003). The author carried out all data gathering and analysis in this chapter, but Keith was very helpful in discussing the intricacies of the concept of energy value.

The following publications were produced during the course of the research project:

**Journal papers**


Conference papers


## Nomenclature and Abbreviations

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Mirror aperture area</td>
</tr>
<tr>
<td>$A_i$</td>
<td>Nominal cross-sectional area for the fluid conduit (excluding fins)</td>
</tr>
<tr>
<td>$A_{ss}$</td>
<td>Cross-sectional area of the fluid conduit</td>
</tr>
<tr>
<td>$\dot{A}$</td>
<td>Exergy (or Availability)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$C_{p-col}$</td>
<td>Thermal capacitance of the solar collector</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Capital cost</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Net cash flow generated at time $t$</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>$FF$</td>
<td>Fill factor</td>
</tr>
<tr>
<td>$F_H$</td>
<td>Carnavos correction factor</td>
</tr>
<tr>
<td>$F_{dirt}$</td>
<td>Scaling factor for dirt on a mirror</td>
</tr>
<tr>
<td>$F_{shade}$</td>
<td>Scaling factor for shading of a mirror</td>
</tr>
<tr>
<td>$F_{shape}$</td>
<td>Scaling factor for mirror shape error</td>
</tr>
<tr>
<td>$F_{uniformity}$</td>
<td>Scaling factor to account for the effect of non-uniform radiation on electrical output</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity $= 9.81 \text{ m/s}^2$</td>
</tr>
<tr>
<td>$\dot{G}$</td>
<td>Radiation flux intensity</td>
</tr>
<tr>
<td>$\dot{G}_T$</td>
<td>Total (direct and diffuse) radiation intensity</td>
</tr>
<tr>
<td>$\dot{G}_{d}$</td>
<td>Direct beam radiation flux intensity</td>
</tr>
<tr>
<td>$Gr$</td>
<td>Grashof number</td>
</tr>
<tr>
<td>$h$</td>
<td>Specific enthalpy</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Heat transfer coefficient for convection</td>
</tr>
<tr>
<td>$I$</td>
<td>Local radiation flux intensity</td>
</tr>
<tr>
<td>$J$</td>
<td>Current</td>
</tr>
<tr>
<td>$J_0$</td>
<td>Dark current, or reverse saturation current</td>
</tr>
<tr>
<td>$J_L$</td>
<td>Light generated current</td>
</tr>
<tr>
<td>$J_{mp}$</td>
<td>Current at the maximum power point</td>
</tr>
<tr>
<td>$J_{sc}$</td>
<td>Short circuit current</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$k_b$</td>
<td>Boltzmann’s constant $= 1.381 \times 10^{-23} \text{ J K}^{-1}$</td>
</tr>
<tr>
<td>$k_d$</td>
<td>Discount rate</td>
</tr>
<tr>
<td>$K$</td>
<td>Extinction coefficient</td>
</tr>
<tr>
<td>$kT/q$</td>
<td>Thermal voltage $= 0.02586 \text{ V (300 K)}$</td>
</tr>
<tr>
<td>$L$</td>
<td>Characteristic length</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow of fluid</td>
</tr>
<tr>
<td>$n$</td>
<td>Refractive index</td>
</tr>
<tr>
<td>$n_p$</td>
<td>Lifetime of a project</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$P$</td>
<td>Perimeter of a fluid conduit</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Nominal wetted perimeter for the fluid conduit (excluding fins)</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$q$</td>
<td>Elementary charge $= 1.602 \times 10^{-19} \text{ C}$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Energy</td>
</tr>
<tr>
<td>$Q_{eq.elec}$</td>
<td>Equivalent electrical energy</td>
</tr>
<tr>
<td>$\dot{Q}_{th}$</td>
<td>Thermal output power</td>
</tr>
<tr>
<td>$\dot{Q}_{elec}$</td>
<td>Electrical output power</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>Rate of (heat) energy transfer</td>
</tr>
<tr>
<td>$\dot{Q}_{rad}$</td>
<td>Thermal heat loss due to radiation</td>
</tr>
</tbody>
</table>
Solar radiation incident upon the receiver
Radiation absorbed by the solar cells
Radiation absorbed in the glass-silicone cover
Thermal heat loss due to radiation from the glass surface
Thermal heat loss due to convection loss from the glass surface
Thermal heat transfer through the insulation
Thermal heat loss due to convection loss from the insulation cover
Thermal heat loss due to radiation from the insulation cover
Thermal resistance for conduction
Thermal resistance for convection
Reynolds number
Series resistance
Shunt resistance
Specific entropy
Time
Environmental temperature
Fluid temperature
Film temperature (the average of the fluid and surface temperatures)
Surface temperature
Overall heat transfer coefficient = k/t
Mean fluid velocity
Wind speed
Velocity of fluid
Open circuit voltage
Voltage at the maximum power point
Height
Absorption
Helix angle of the fins = 0 for the CHAPS receiver
Temperature coefficient for the relationship between solar cell efficiency and temperature
Thickness
Azimuth angle
Small time interval
Emissivity of glass
Primary-energy saving efficiency
Conversion efficiency of a conventional thermal power station
Thermal efficiency
Electrical efficiency
Angle of incidence of radiation
Escape angle for Total Internal Reflection
Zenith angle
Dynamic viscosity
Dynamic viscosity evaluated at the wall temperature
Kinematic viscosity = \( \mu/\rho \)
Reflectivity
Stefan-Boltzmann constant
\( = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4} \)
Transmission-absorption product
Transmissivity
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM0</td>
<td>Air Mass 0, referring to the spectral distribution of sunlight outside the atmosphere</td>
</tr>
<tr>
<td>AMx</td>
<td>Air Mass 1.5, referring to the spectral distribution of sunlight when the sun is at angle $\cos^{-1}(1/x)$ from vertical</td>
</tr>
<tr>
<td>ANU</td>
<td>Australian National University</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of system</td>
</tr>
<tr>
<td>CHAPS</td>
<td>The Combined Heat and Power Solar collector</td>
</tr>
<tr>
<td>CPC</td>
<td>Compound Parabolic Concentrator</td>
</tr>
<tr>
<td>CSES</td>
<td>Centre for Sustainable Energy Systems, at the Australian National University</td>
</tr>
<tr>
<td>CSR</td>
<td>Circumsolar Ratio</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>EQE</td>
<td>External Quantum Efficiency</td>
</tr>
<tr>
<td>FES</td>
<td>Fractional Energy Saving</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GOML</td>
<td>Glass On Metal Laminate - the material used to fabricate CHAPS mirrors</td>
</tr>
<tr>
<td>HWS</td>
<td>Hot water system</td>
</tr>
<tr>
<td>LEC</td>
<td>Levelised energy cost</td>
</tr>
<tr>
<td>LGBG</td>
<td>Laser Grooved Buried Grid</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum power point tracker</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>PT100</td>
<td>Temperature sensor using a platinum resistive device</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>PV/T</td>
<td>Combined Photovoltaic / Thermal</td>
</tr>
<tr>
<td>SEF</td>
<td>Solar Energy Fraction</td>
</tr>
<tr>
<td>SHWS</td>
<td>Solar hot water system</td>
</tr>
<tr>
<td>SRCC</td>
<td>Solar Rating and Certification Corporation</td>
</tr>
<tr>
<td>TK</td>
<td>Thermocouple Type K</td>
</tr>
<tr>
<td>TRNSYS</td>
<td>A TRaNsient SYStem simulation program, used for solar system simulations</td>
</tr>
</tbody>
</table>
# Table of contents

Declaration................................................................................................................. iii
Acknowledgements................................................................................................. v
Abstract.................................................................................................................... vii
Foreword.................................................................................................................... ix
Nomenclature and Abbreviations........................................................................... xi

## Nomenclature
Nomenclature........................................................................................................... xi
Abbreviations........................................................................................................... xiii

## Table of contents

### Introduction

1.1 Energy today................................................................. 1
1.2 Solar energy.............................................................. 2
1.3 Objectives of this work................................................... 2
1.4 Thesis structure.......................................................... 3

### Background

2.1 The sun................................................................. 7
2.2 Photovoltaics............................................................. 8
2.2.1 Concentrator solar cells........................................ 11
2.3 Concentrator photovoltaic systems.............................. 13
2.4 Solar thermal.......................................................... 16
2.5 Combined photovoltaic – thermal.................................... 19
2.5.1 Water cooled PV/T........................................ 20
2.5.2 Air cooled PV/T collectors................................. 21
2.5.3 Concentrating PV/T collectors............................ 21
2.6 Introduction to TRNSYS............................................. 23
2.7 Heat transfer theory.................................................. 24
2.7.1 Convective heat transfer for internal flow................. 24
2.7.2 Convective heat transfer for external flow.............. 25

### Energy Value Comparison

3.1 Introduction............................................................... 27
3.2 Thermodynamic valuation........................................... 28
3.2.1 Energy.............................................................. 28
3.2.2 Primary-energy saving......................................... 28
3.2.3 Exergy............................................................. 29
3.3 Economic valuation.................................................... 30
3.3.1 Open Market Approach........................................ 30
3.3.2 Renewable Energy Market Approach.................. 32
3.3.2.1 Grid-connected photovoltaics levelised energy cost ............................................. 33
3.3.2.2 Solar hot water levelised energy cost ................................................................. 34
3.4 Environmental valuation ....................................................................................... 37
3.4.1 Avoided emissions ............................................................................................. 37
3.4.2 Life cycle emissions .......................................................................................... 38
3.5 Comparison of methods ....................................................................................... 39
3.6 Optimisation methodology ................................................................................... 40

The CHAPS system Chapter 4 ..................................................................................... 41
4.1 Solar cells .............................................................................................................. 42
4.2 Mirrors .................................................................................................................. 42
4.3 Receivers .............................................................................................................. 44
4.3.1 Evolution of the design ..................................................................................... 44
4.3.2 Summary of the current design ......................................................................... 45
4.3.3 Receiver sub-components .................................................................................. 46
4.4 Sun tracking ......................................................................................................... 47
4.4.1 Single-axis versus two-axis tracking ................................................................ 48
4.4.2 Tracking tolerance ........................................................................................... 51
4.5 Spectral dependency ............................................................................................. 53
4.5.1 Transmission through the cover ....................................................................... 53
4.5.2 Measurement of transmission, reflection and absorption .................................. 56
4.5.3 Results of spectrophotometer measurements .................................................... 56
4.5.4 Spectral dependency of the mirror reflection ...................................................... 57
4.5.5 Spectral dependency of the glass transmission .................................................. 58
4.5.6 Spectral dependency of the silicone transmission ............................................. 60
4.5.7 Glass-silicone cover reflection .......................................................................... 61
4.5.8 Spectral dependency of the solar cell absorption ............................................. 62

Thermal Performance Chapter 5 .................................................................................. 65
5.1 Experimental method .......................................................................................... 65
5.1.1 The mirror ...................................................................................................... 65
5.1.2 The receiver ................................................................................................... 66
5.1.3 Data logging equipment .................................................................................. 66
5.1.3.1 Data Logger ................................................................................................ 66
5.1.3.2 Direct beam radiation .............................................................................. 66
5.1.3.3 Ambient temperature ............................................................................... 66
5.1.3.4 Wind speed .............................................................................................. 67
5.1.3.5 Inlet water temperature ........................................................................... 67
5.1.3.6 Temperature difference across the receiver ............................................... 67
5.1.3.7 Volumetric flow ....................................................................................... 67
5.1.3.8 Current and voltage ................................................................................ 68
5.1.3.9 Temperature of the receiver body ............................................................. 68
5.2 Measured efficiency ............................................................................................ 69
5.2.1 Range of conditions ....................................................................................... 71
5.2.2 Error .............................................................................................................. 71
5.2.3 Discussion ...................................................................................................... 71
5.3 Heat transfer between the receiver and the fluid ................................................................. 73
  5.3.1 Determination of the rate of heat transfer in a receiver .............................................. 74
  5.3.2 Results and correlations for internal fins ......................................................................... 75
5.4 Heat transfer from the surface of the receiver ................................................................. 77
  5.4.1 Radiative heat transfer ....................................................................................................... 77
    5.4.1.1 Measurement of glass temperature .............................................................................. 78
    5.4.1.2 Calculation of radiation losses ..................................................................................... 78
  5.4.2 Convective heat transfer .................................................................................................. 80
    5.4.2.1 Free convection ............................................................................................................ 80
    5.4.2.2 Forced convection ......................................................................................................... 80
    5.4.2.3 Mixed convection ........................................................................................................ 81
    5.4.2.4 Convection calculations for a CHAPS receiver ........................................................ 81
5.5 Heat transfer within the receiver materials ........................................................................ 84
  5.5.1 Measurement of thermal resistance tests for various heat sinking tapes ....................... 84
  5.5.2 Other materials .............................................................................................................. 87
  5.5.3 Measured losses through the insulation ......................................................................... 87
6  Simulation of the conduction using Strand7 ........................................................................ 88
  6.1 Energy input ....................................................................................................................... 89
  6.2 Energy loss ........................................................................................................................ 90
  6.3 Base case ............................................................................................................................ 91
  6.4 Validation ........................................................................................................................... 92
  6.5 Sensitivity analysis .............................................................................................................. 94
  6.6 Results of the Strand7 modelling ....................................................................................... 98
    6.6.1 Wind speed and direction ............................................................................................... 98
    6.6.2 Fluid temperature and flow rate .................................................................................... 99
    6.6.3 Conductivity of the thermal tape ............................................................................... 99

Electrical Performance  Chapter 6............................................................................................. 101
6.1 Temperature dependency .................................................................................................... 101
  6.1.1 Measurement of I-V curves using the flash tester ......................................................... 101
  6.1.2 Temperature dependency results from flash tester measurements ............................... 102
  6.1.3 Temperature dependency results from a full receiver .................................................. 103
6.2 Illumination profile .............................................................................................................. 104
  6.2.1 The sun shape ............................................................................................................... 105
6.3 Non-uniform illumination in the transverse direction ...................................................... 106
  6.3.1 Modelling the effect of a non-uniform illumination profile .......................................... 106
  6.3.2 Experimental comparison with the model ..................................................................... 109
6.4 Non-uniform illumination in the longitudinal direction ................................................... 111
  6.4.1 The ‘Skywalker’ module - measurement of the longitudinal flux profile ................... 112
  6.4.2 Results from the skywalker module ............................................................................. 113
    6.4.2.1 Comparison of mirrors ............................................................................................... 113
    6.4.2.2 Results from a single mirror for a range of incidence angles .................................. 115
    6.4.2.3 Attenuation of peaks and troughs ............................................................................. 117
  6.4.3 Shape error of the mirror ............................................................................................... 118
  6.4.4 The effect of slope error on the reflected flux profile .................................................... 121
  6.4.5 Ray tracing – simulation of the longitudinal flux profile ............................................ 124