EVALUATION OF ELECTRICAL AND THERMAL PERFORMANCE OF A ROOFTOP-FRIENDLY HYBRID LINEAR CPV-T MICRO-CONCENTRATOR SYSTEM

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ABSTRACT

A low concentration, linear, hybrid micro-concentrator system has been developed for urban rooftop installation. The system produces both electrical and thermal power, integrating the roles generally taken by separate flat plate photovoltaic and solar hot water systems. Initial test results without any system optimisation has demonstrated an electrical output of at least 305 W, and a thermal output of 1580 W. The micro-concentrator system is constructed from standard industry components including modified mono-crystalline silicon one-sun solar cells, typically used in flat plate applications. The manufacturing processes have been designed to incorporate low cost methods, and tap directly into existing economies of scale.

Keywords: Micro-concentrator, CST, PV-Thermal hybrid

1. INTRODUCTION

Concentrating photovoltaic (CPV) systems offer several advantages over flat plate photovoltaic (PV) systems. These advantages include the replacement of costly solar cells with inexpensive optics and tracking systems to reduce the overall system cost in terms of $/kWh. CPV systems also offer the opportunity to capture what would otherwise be waste heat from the cells and receivers in the form of CPV-thermal (CPV-T) systems. These CPV-T systems are integrated electrical and thermal systems that produce both electrical and thermal energy. However, CPV and CPV-T systems are traditionally significant structural installations, making them generally unsuitable for domestic and commercial rooftop installations.

Utility scale power generation is already being demonstrated in larger ground-mounted systems using high concentration photovoltaic technology. In these high concentration applications, very expensive specialist solar cells are placed under high concentration ratios up to 1000X [1]. In comparison, only quite limited research and development of systems for small-scale urban rooftop environments has been undertaken on a global scale. Urban markets, particularly domestic markets, would be well served by low-concentration systems of up to 30 to 50 suns. By reducing the concentration ratio the demands on optics, tracking, thermal management, and maintenance are significantly reduced in comparison to high concentration systems. However, low-concentration systems suffer from a lack of specialized reasonably-priced, commercially-available solar cells at industrial volumes [2]. One possible approach to sidestep this problem is to use modified mono-crystalline silicon solar cells designed for one-sun operation; but where the modification allows the system to still achieve sufficiently high efficiencies at low concentration ratios.

In order to enter the rooftop urban market, CPV systems need to be low maintenance, reliable, easy to operate, and to be able to be readily and economically rooftop mounted. The tracking and optical systems need to be sufficiently precise and reliable for the system to be able to operate for 25 years or more, and the material, construction, and installation costs need to be kept to a minimum. In standard linear CPV systems, which are often used for low concentration applications, the large open areas of the optical system are exposed to hail, snow, rain, dust, and other soiling sources. The conventional optical systems are generally quite heavy and robust in order to provide the required rigidity and focal performance, so they generally require significant structural support. This places additional load on the tracking system. The entire exposed system is subject to large wind loading, and must be manufactured to high tolerances to ensure flux uniformity on the receiver in the presence of distortion by gravitational loading, wind loading, and thermal expansion [3],[4]. These requirements mean that the systems are generally significant structural installations. In addition, economies of scale with conventional linear concentration systems have yet to be realized; hence any technology that can make use of existing industrial production technologies is likely to have a significant cost and performance advantage.

A joint research venture between the Centre for Sustainable Energy Systems at the Australian National University and Chromasun Inc., a San Jose-based start-up company, has developed a hybrid, linear CPV-T system designed specifically for urban domestic and industrial rooftop applications [5]. This system is known as a micro-concentrator (MCT) system, and the development was motivated by the benefit of on-site generation of both thermal and electrical energy with a greater combined efficiency and reduced footprint than independent PV and solar hot water systems. This paper presents an overview of the MCT system, a discussion of the receiver design and fabrication, and initial results from a full hybrid system.

2. THE MICRO-CONCENTRATOR (MCT) SYSTEM

The basic approach taken with the development of the MCT system was to reduce the size and weight of all components, while incorporating the entire functional system into a low-profile, sealed enclosure which can be treated as a ‘black box’ in order to simplify installation and maintenance.

Fig 1: Three MCT units mounted on a demonstration rooftop. The light-weight, low area-loading MCT systems were mounted on the same supporting frame as the surrounding flat-plate PV panels.

There are two broad options for the concentrator system receiver: it can be either thermal only, which provides a thermal output at up to 220 ºC, suitable for solar cooling of commercial buildings, or it can be a hybrid CPV-T that allows for both electrical and thermal energy outputs, with the thermal output temperature suitably limited by the PV element operational requirements. The compact form of the MCT, and the identical enclosure and optical and tracking system designs for both CPV and CPV-T applications, allows the MCT units to be installed in a modular fashion. For any given installation, both thermal only and hybrid CPV-T systems are able to be installed on the one site in a demand-specific configuration providing a suitable mix of electrical and thermal energy. MCT units can be densely packed in a similar fashion to flat plate PV systems, and can be mounted on the same supporting frame as PV panels, as is shown in Figure 1.

One of the key design features of the MCT system is the sealed enclosure. This enclosure is 3.0 m long, 1.2 m wide, and 0.3 m deep, and isolates all the functional components of the system, including the mirrors, tracking system, and receiver elements from external environmental influences such as wind loading, humidity, and soiling. The removal of the effect of wind loading on the optical system allows the use of a Fresnel array of ultra-lightweight reflectors, as shown in Figure 2, that requires no structural support, stiffening, or bracing elements other than tensioning at the mirror-mounting points at each end of the enclosure.

Fig 2: The array of lightweight Fresnel reflectors, each individually tensioned at the end mounting points, operating on-sun showing the focal pattern of the array on the MCT end-plate.

By almost entirely eliminating internal supporting structures, the material, manufacturing, and assembly costs of the system are significantly reduced. The dramatic simplification of the optical system, and also the tracking system, enables the entire MCT system to have a low weight with an area loading less than 30 kg/m2, making it suitable for general rooftop installation, including most domestic roofs, with no structural alteration required. The sealed enclosure is also aesthetically designed for broad consumer appeal. The isolation of the system components from the external environment increases the lifetime of the system, and reduces or eliminates maintenance costs normally associated with linear concentration systems with exposed elements. The system construction can occur off-site, with installation carried out in a similar fashion to that of installing flat plate PV and solar hot water systems.

2. MCT HYBRID RECEIVERS

The MCT hybrid receivers consist of a series of sub-module assemblies thermally bonded to the base of a channel in an aluminium extrusion which incorporates a cooling fluid channel along the rear of the extrusion. The cooling fluid is used to cool the cells, extracting the thermal energy for applications such as domestic water heating. Once bonded to the extrusion the sub-modules are electrically interconnected and then the entire receivers are encapsulated to protect the cells and to increase light absorption. Finally, the completed receivers are mounted at the line focus in the enclosure.

3.1 Hybrid Receiver PV cells

One of the fundamental problems hampering the commercial development of low to medium concentration CPV systems is the lack of commercially available cells suitable for these linear concentrator applications. When planning the MCT system, a strategic design decision was taken that, rather than using expensive cells specifically designed for operation under concentration, commercially available, high-efficiency, one-sun solar cells would be modified for use under concentration. A significant amount of development work has now enabled the delivery of suitably modified one-sun cells that have efficiencies in the range of 19 to 20% at the expected concentration ratio of 15 to 30 suns.

3.2 Sub-module elements

These modified one-sun solar cells are integrated into a sub-module using a monolithic substrate that incorporates structural support for the cell array, heat sinking of individual cells, electrical interconnection between cells and adjacent substrates, and integrated bypass diode protection of individual series-connected cell strings.

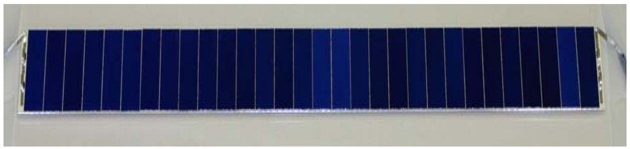

Fig. 3: A sub-module incorporating 30 modified one-sun solar cells heat-sunk and surface mounted onto a monolithic substrate, with integrated bypass diode protection.

By surface mounting the cells using a custom reflow process, sub-modules such as that shown in Figure 3 are produced with inter-cell spacing as little as 100 μm.

3.3 Thermal Interface

Ten substrates, with 30 cells on each substrate, were mounted linearly in each receiver. In order to ensure good thermal contact and efficient heat transfer between the substrates and the extrusion, the substrates were bonded to the extrusion using a highly thermally conductive adhesive. The thermal adhesive was syringe-dispensed in a carefully controlled manner that ensured the correct quantity of adhesive was deposited in the correct location. This step is important in order to establish good thermal contact across the interface, while at the same time ensuring the avoidance of excess adhesive. Excess adhesive could be extruded out of the gap during the clamping process, potentially shading the cells. The assembled substrates were then placed on top of the adhesive and sequentially clamped, as shown in Figure 4.

Fig. 4: Sub-modules mounted and clamped in the extrusion channel. Clamps were used to hold the sub-modules in place and to prevent bowing of the assemblies during the thermal curing process.

In order to correctly cure the thermally conductive adhesive, a heating fluid was circulated through the back of the receiver.

The heating fluid comprised a mix of water and another liquid, so the combination could provide a 100 ºC curing temperature without the risk of the fluid boiling. A 3 metre long curing chamber was constructed using an insulated length of aluminium pipe to keep the temperature profile uniform along the length of the receiver. Using this cheap and effective arrangement, the adhesive was cured for the required 90 minutes at 100 ºC.

Following the curing process, the system was allowed to cool, and the fluid was drained from the receiver pipe. The individual sub-modules were then electrically interconnected in series by soldering the tabs at the end of each board. Hi-pot tests were performed to ensure that there was no leakage current between the electrical components and the aluminium extrusion.

3.4 Receiver Encapsulation

In order to protect the receivers from the external environment, and to increase the efficiency of the cells by suitable refractive index-matching, the receivers were encapsulated using optically clear silicone gel covered with a sheet of 1 mm thick glass. These materials are used in a number of industrial solar module encapsulation processes, and are designed to provide maximum transmission of light through the encapsulant and maximum absorption of light by the solar cells.

The anti-reflection coating of the solar cells is optimised for encapsulants with a refractive index around 1.4. When correctly encapsulated, the efficiency rises by around one percentage point absolute compared with a similar arrangement tested in air. A combination of efficiency increase and improved protection of the cells makes the encapsulation process economically worthwhile.

The encapsulation procedure was performed in three stages. The purpose of the first encapsulation was to ensure that the silicone flowed completely under the cells, preventing air being trapped under the cells and creating voids which could produce de-lamination sites. This process was conducted using a purpose-built vacuum chamber. The receiver was tilted at 15º to the horizontal, which allowed silicone to be poured along one edge of the cells in the groove of the channel. The receiver, at a tilt of 15º, was then introduced into the vacuum chamber, which was then sealed and evacuated. Under vacuum, the air was removed from the area under the cells. When all the air was removed, the receiver was then tilted back to the horizontal and the silicone flowed across and under the cells, sealing the top surface. When the system was brought back up to atmospheric pressure, the silicone is forced into all the previously evacuated areas, fully encapsulating the cells. The quantity of silicone poured in the channel was calculated in order to allow 2 mm of clearance coverage over the cells once the receiver was tilted back to the horizontal. This quantity of silicone meant that only one edge of the cells was covered when the receiver was tilted at 15º.

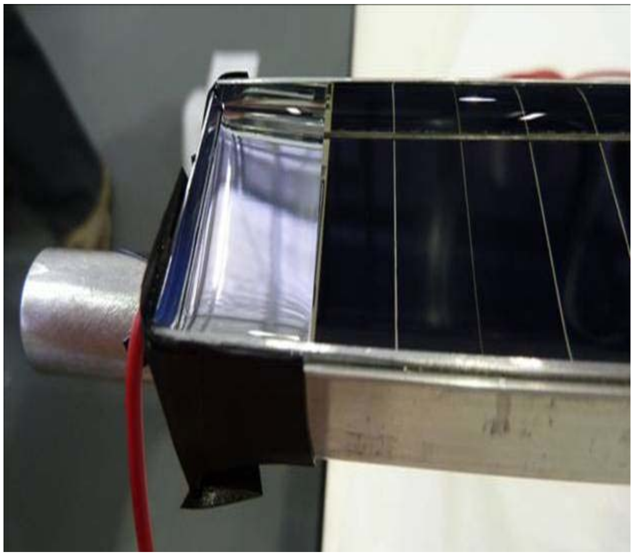

Fig. 5: An end view of a receiver during the second encapsulation, showing the Alanod protective strip covering sensitive components.

The second encapsulation step was used to lay protective Alanod strips over the diodes and leads, and to raise the level of the silicone encapsulant to just below the total height of the side-wall Alanod. Figure 5 shows a view of the end of one receiver during the second encapsulation. The Alanod strip covers the bypass diodes at the ends of each of the sub-modules, within the receiver, and the exposed board ends and leads at the ends of the receiver. The Alanod shield prevents damage to these components, which would otherwise be burnt under concentrated illumination.

Once the second encapsulation was set, the third encapsulation step was used to lay the cover glass on the receiver. The level of encapsulant was calculated so that the top of the cover glass sat level with the top of the receiver sidewall. The glass was laid in sections, with each piece being the same length as the sub-modules. This length and location was designed to avoid shadows from the glass ends being projected onto a cell. By first allowing the second encapsulation to set prior to commencing the third step, the glass was prevented from sinking through the silicone. This process is being simplified for future assemblies.

3.5 Receiver Mounting in the MCT

The receivers were placed in the MCT box channel mounts, and the system was plumbed such that the coolant fluid went through one receiver, then across into the second receiver, and then out the same end of the box as the entry. The two receivers were electrically connected in series to create a high voltage, low current system. An alternative is to connect the receivers in parallel, in order to reduce the effects of optical mismatch. An image of a receiver mounted in an open box is shown in Figure 6.

Fig. 6: A completed receiver mounted in open box, with plumbing and electrical interconnection completed.

4. INITIAL MCT TESTING

Prior to mounting in the MCT box, the completed receivers were tested at close to one sun illumination. Each receiver produced an open circuit voltage of approximately 190 V, and a short circuit current of approximately 108 mA. The operation of the bypass diodes was checked by shading areas of the module and checking that the short circuit current remained unaffected.

Figure 7 shows the enclosed system on-sun and tracking during the testing procedure. Several sets of preliminary measurements were performed, with an incident global irradiation of just over 1 sun. A combination of manual methods were used to take the data because the purpose-designed test system required for high-voltage IV curve measurement was not yet completed.

Fig 7: The prototype hybrid CPV-T MCT system on-sun and tracking.

It should be noted that the measurements reported here provide an indication only of system performance. A digital multi-meter was used to measure the open circuit voltage and short circuit current, and a temporary system with a manually variable load was used to measure a few extra operating points to generate an indicative IV curve. An example of a current voltage curve taken during measurement is shown in Figure 8.

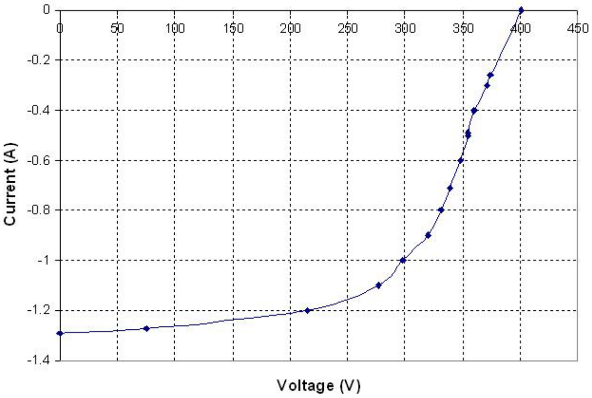

Fig 8: A manually measured and generated current-voltage characteristic of the MCT CPV-T prototype.

The two different measurement techniques, and the small number of data points, resulted in a curve on which not all data points fall on the expected curve. Due to the end effects of a receiver with the angle of incidence of the MCT not optimised, at least one sub-module was not operational. However the small number of data points does not allow the operation of the bypass diode to be observed on this manually-generated IV curve. The electrical power output of the system under this operation mode, calculated from a point on the curve estimated to be the maximum power point was approximately 305 W. The thermal output was calculated from the coolant flow rate, heat capacity, and the temperature difference between inlet and outlet, and did not allow for any losses. The measured thermal output using this method was approximately 1580 W.

These results were taken without any optimisation of flow rates, and without any optimisation of the angle of orientation of the system. The end effects alone could account for around a 10% decrease in measured performance compared with expected system performance. A dedicated control and data acquisition system that will continuously monitor the system performance over time, and under varying operating controls and simulated loads, is under development. This prototype system will be mounted on the roof-top test area adjacent to the CSES laboratories. A second system, with design improvements, is under construction.

6 CONCLUSION

Fully-functional hybrid CPV-T receivers that were developed at ANU have been demonstrated in a Chromasun MCT system. The receivers are based on commercially-available one-sun solar cells that have been modified to operate under concentration. The monolithic sub-module assemblies with integrated heat-sinking and bypass diodes are designed for high electrical and thermal performance using modified industry-standard materials and slightly adapted assembly processes. The design and assembly procedures have been specifically developed to incorporate low-cost manufacturing processes and materials such that the existing economies of scale can be directly tapped for immediate benefit.

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