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A spectrally splitting photovoltaic-thermal hybrid receiver utilising direct absorption and wave interference light filtering

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ABSTRACT

We have developed a novel spectrally splitting hybrid solar receiver by combining a simple dichroic filter and a liquid channel as a selective absorbing medium. The combination acts as a band pass filter for silicon solar cells. The geometry can be optimised for any linear concentrator; in this paper we have optimised it for a commercially available linear rooftop micro-concentrator. The optics of the concentrator at its focal region has been investigated using ray tracing. A simple 5-layer dichroic filter made of titanium dioxide and silicon dioxide has been designed, optimised, and fabricated with a focus placed on manufacturing simplicity. It has been shown that such a filter directs 54.5% of the concentrated light to the silicon photovoltaic cells; the Si cells considered in this paper can convert 26.1% of this energy into electricity which is significantly higher than their 20.6% efficiency under the full spectrum. This is due to the fact that 73.3% of the incident flux is within the cell's relatively high spectral response range, which can be efficiently converted into electricity. The rest of the spectrum can be collected as high temperature heat. This research shows the possibility of employing low-cost direct absorption-dichroic filtering hybrid receivers in liner concentrators.

1. Introduction

Increasing the efficiency of solar receivers represents a desirable pathway towards reducing the installed cost per Watt, and obtaining higher solar fractions in buildings with limited rooftop areas. Concentrating photovoltaic (CPV) systems and hybrid photovoltaic-thermal receivers can help us to achieve this. High heat loads in CPV systems are considered an opportunity to design a combined heat and power system to deliver electricity and heat concurrently.

Three main methods have been introduced to remove heat from CPV systems: (a) thermal removal, through passively or actively cooled cells [1], (b) device removal, through the use of high efficiency multi-junction cells [2], and (c) optical removal, through spectral modification of the incoming sunlight [3,4]. A combination of these methods can also be incorporated to achieve the best outcome [5]. In the third method, sunlight is separated into two or more spectral bands with each band directed towards an appropriate receiver. For example, the most suitable spectral band for silicon cells as the most common type of PV cells is roughly between 700 nm and 1100 nm [6]. Using spectral beam splitting in concentrating photovoltaic thermal receivers (CPVT) can not only improve the total efficiency [3] of the system but also thermally decouple the thermal receiver from the cell. The latter allows the temperature of the thermal output to increase beyond the maximum operational temperature of the PV cell and to deliver high grade high temperature thermal output in addition to electricity. This may improve the market penetration of solar energy in solar cooling and industrial applications.

Application of spectral beam splitting in solar energy has been extensively studied for CPV systems, e.g. Barnett and Wang [7] designed and optimised a spectral beam splitting PV system using dichroic filtering for GaInP/GaAs, Si, and GaInAsP/GaInAs cells achieving an efficiency of 39.1% at a concentration ratio (CR) of 30. Khvostikov et al. [8] proposed dichroic filtering in combination with AlGaAs, GaAs, GaSb reaching an efficiency of 39.6%. The outcome of the research in this field has been reviewed thoroughly in [3,4]. Applying spectral splitting in CPVT systems has been studied by Chendo et al. [9] and Hamdy and Osborn [10] in detail. They analysed the system performance over the year and

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showed that the reduced heat load on the PV cells improves the electric conversion efficiency of the system. Recently Jiang et al. [11] studied a CPVT parabolic trough system using dichroic filters with 240–400 °C thermal output. However the majority of research in this field is limited to theoretical analyses with a few practical realisation. These devices have been too expensive to be commercially viable for linear concentrators. Wave interference [12,13] and selective absorption [9] filters can be used for spectral separation in CPVT systems. Wave interference filters employ a number of high and low refractive index transparent materials (multilayer thin film filters) or a transparent layer with continuously varying refractive index (rugate filters) deposited on a substrate to generate the light filtering effect. Selective absorbers use pure liquids, solution mixtures [9,14], nano-fluids [15,16], or solid state optical filters to filter out the desired spectral band(s).

Wave interference filters provide more flexibility compared to selective absorbers [12]. Such filters can be broad band-pass which are made of one or two edge filters in combination. These two edge filters (a long and a short pass) can be deposited on either side of a substrate. A concern in such band pass filters is to combine them in such a way that one edge filter does not create transmission peaks in the rejection band of the other [17]. However, they normally consist of a large number of layers to produce an effective broadband filtering effect, but this results in higher cost.

In this work, we propose a hybrid photovoltaic-thermal (CPVT) receiver in a linear Fresnel concentrator incorporating a selective absorber together with a wave interference filter (a dichroic mirror), acting as a band pass filter. A simple filtering structure that is introduced is relatively facile and low cost to manufacture. The proposed configuration takes advantage of direct solar absorption that has been studied by Minradi [18] and Otanicar [19,20] to simplify the structure of the required dichroic coating. The details of the design are given in the next section where we present an optical analysis of the whole system and discuss the advantages of using the proposed configuration.

2. Design description

In this paper, the term hybrid collector refers to the combination of a rooftop linear micro-concentrator (LMC) and a CPVT receiver installed at its focal axis. In this section, we briefly introduce the proposed hybrid receiver design and then discuss its applicability in an LMC hybrid collector.

2.1. The hybrid receiver design

The proposed hybrid receiver consists of a high temperature (above 150 °C) liquid channel optically coupled to high efficiency back contact crystalline silicon (Si) cells that have been optimised for concentrating photovoltaic (CPV) applications [21]. The overall configuration of the receiver is shown in Fig. 1. Concentrated light propagates in the upward direction and enters the receiver through the front glass. It passes through this highly transparent glass and enters the semi-transparent liquid flowing inside the channel. The liquid serves as a heat transfer fluid as well as a spectral filter. Vivar and Everett [14] have provided a review on optical and heat transfer properties of a range of liquids for such an application. Candidate liquids considered in this paper are water, propylene glycol, and ethylene glycol. The optical properties of these liquids will be discussed in the following sections.

The liquid channel acts as a short pass filter with a cut-off wavelength at near infrared, e.g. 1200 nm. Shorter wavelengths first pass through both the liquid and the highly transparent rear glass with negligible attenuation, and then land on the dichroic coating at the top face of the rear glass. This coating acts as a long pass filter, reflecting all wavelengths shorter than 600 nm and transmitting the remainder of the spectrum. The reflected and transmitted rays are absorbed by the absorbing side walls and the PV cells, respectively. The silicone layer between the rear glass and PV cells is required to achieve a better refractive index match between the various layers to minimise the reflection losses. It also provides a high thermal resistance between the hot channel and the PV cells.

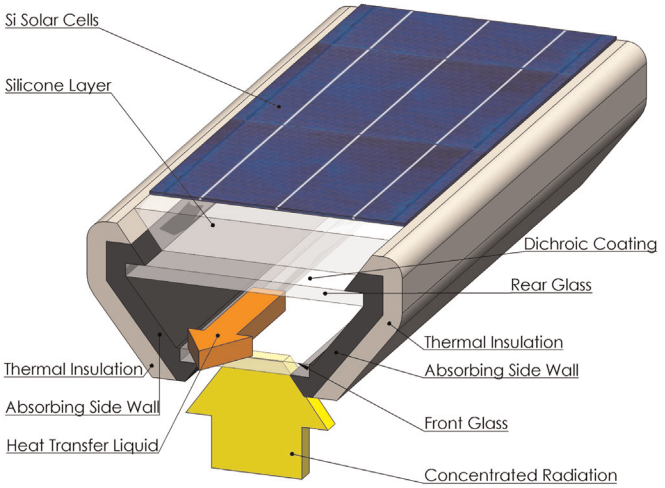

Fig. 1. Concentrated light enters the receiver through the front glass and is filtered by the dichroic coating at the top side of the rear glass. The filtered light is sent to the PV cells and the rest is absorbed by the side walls or directly in the fluid.

The absorbing side walls are made of metal for better heat transfer across the wall with a highly absorbing coating on their surface. It is important to note that this surface does not need to be a selective surface because it is in direct contact with the liquid layer that absorbs all infrared thermal emission from the hot surface. The outside of the absorbing side walls is thermally insulated.

3. Methods

3.1. The rooftop linear micro-concentrator (LMC)

The LMC is a one-axis solar tracking concentrator developed and commercialised by Chromasun Pty Ltd [22–24]. It comprises two sets of Fresnel reflectors, each set with 10 curved mirrors, encapsulated inside a glass canopy. The mirrors are controlled by a tracking system to focus the sunlight on a central axis 25 cm above the mirror plane. The whole collector is 3.3 m long, 1.2 m wide and 0.3 m high. The glass canopy protects the internal components from wind, dust and water. Fig. 2(a) and (b) shows a schematic of the LMC. Fig. 2(c) is the cross-sectional view showing ray tracing conducted for the LMC under normal angle of incidence on the box. This concentrator has been optimised for high temperature (100–220 °C) thermal applications and has been recently retrofitted for combined heat and power generation by installing highly efficient silicon cells coupled to a cooling channel [25,26].

The LMC provides the hybrid receiver with concentrated radiation and the hybrid receiver transforms it into useful electrical and thermal energy. To estimate the overall performance of the system, the whole configuration has been analysed as an integrated package.

The orientation of the LMC, sun angle, shadows from the structure on the mirrors, and the geometrical arrangement of the mirrors can affect the spatial and angular distribution of light at