Experimental Thermal and Electrical Characterization of a Novel Spectral Beam Splitting Low-Concentrating Photovoltaic Thermal Collector

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Abstract

The effect on the thermal and electrical performance of a low-concentrating photovoltaic-thermal LCPVT collector due to the implementation of a spectral beam splitter SBS and a secondary thermal receiver is experimentally investigated. The SBS was made with a commercial spectral film filter, and it was installed in front of the PV cells of the triangular PVT receiver of the LCPVT that is cooled with water. The SBS has the function of transmitting most of the wavelengths of the solar spectrum that are used for the PV cells to generate electricity reflecting the rest of the spectrum to a secondary thermal absorber where water can be heated to higher temperatures. The total thermal efficiency of the LCPVT with the SBS filter and the secondary thermal absorber was 45%. Electrical efficiency was reduced from 7.3% for the case of LCPVT without SBS filter to 2.7 % for the case of using the SBS filter and secondary thermal receiver. Reduction of efficiency is attributed to optical losses, radiation blockage and the non-optimal response of the spectral film employed. The proposed design of SBS could reduce the surface temperature of the PV cells by 10 °C compared to the case without the filter, and the difference of temperature between the inlet and outlet of the secondary thermal absorber could be increased 13.5 °C by reducing independently the mass flow from the PVT receiver. The technical feasibility of the proposed SBS filter configuration using inexpensive commercial filters was experimentally proved with the potential to generate heat of higher temperature maintaining low temperatures for the PV cells.

Keywords: hybrid photovoltaic thermal, parabolic low-concentrating trough, spectral splitting, PVT, Dichroic filter, secondary thermal receiver.

1. Introduction

Concentrating Photovoltaic/Thermal (CPVT) collectors are relatively recent solar technology that is entering the market due to the capacity to generate simultaneously thermal and electrical energy. In this type of collector, the absorber of a conventional Parabolic Through Concentrator (PTC), is replaced by a receiver with photovoltaics (PV) cells that are cooled by a fluid. PTC is one of the most employed technologies to provide heat of high temperature for power generation and heat of low and medium temperature for industrial processes (Tagle-Salazar et al. 2020). Meanwhile CPVT collectors still need to overcome some obstacles before it can become a feasible alternative for the industry to provide heat of higher temperature for their processes. In this type of collector, the concentrated solar radiation increases the surface temperature of the PV cells, decreasing

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their efficiency and limiting the CPVT to operate at temperatures below 90°C to avoid deterioration of the cells. To solve this problem, solid and liquids filters that works as spectral beam splitters (SBS) have been developed to select the wavelengths from the solar spectrum with the purpose to decouple the thermal and electrical processes (Ju et al. 2017). Solid filters let pass wavelengths in the range that are more appropriated to the PV cells for the generation of electricity such as the visible, part of the ultraviolet and near infrared (NIR), while the rest of the spectrum is directed to a thermal receiver where a fluid can be heated to higher temperatures without affecting the performance of the PV cells. Liquid filters use a channel with a semitransparent liquid to absorb the UV and most of the IR radiation, letting only visible radiation pass to the PV cells. In the last decade, research has been performed to experimentally evaluate the effect on the performance of the CPVT due to the implementation of SBS filters. Some of the most relevant works are described below.

Raush et al. (2014) experimentally evaluated a modified solar thermal concentrator where a PV module and a cold mirror were installed to hybridize the collector applying spectral filters. Reflected solar radiation range was 500-1000 nm with 30x concentration factor for PV module, while the rest of radiation with 104x concentration factor was for the thermal receiver. Test bench used empirical values as open circuit voltage, short circuit current and fill factor to calculate the maximum point of power. Initial thermal efficiency (without PV module) of the collector was 70-80% in the best conditions, exchanging 9 points of thermal efficiency for 30% of electrical efficiency in PV modules (latter efficiency being based on reflected radiation only). System achieved an increase of 22.5% in solar to electrical efficiency. Widyolar et al. (2019) simulated and developed a two stage CPVT collector using a combination of parabolic trough and compound parabolic concentrators, with double junction InGaP/GaAs solar cells, and using suspended solid particulate (alumina based) as heat transfer fluid. The collector was operated at 600 °C due to its capabilities of 50x concentrations. Optical efficiency was confirmed to be correct (64% experimentally), obtaining a thermal efficiency of 15% and electrical efficiency of 4% operating at 600 °C. Wingert et al. (2020) evaluated experimentally the use of spectral filters in a CPVT, using crystalline silicon PV cells in a secondary receiver, reflecting to this receiver 71% of the sunlight (between 480 and 1120 nm) and transmitting the rest to a thermal receiver. Results demonstrated 3% average electrical efficiency (based on aperture area of the collector), while thermal efficiency is not reported, but a 13% increase was obtained over the baseline performance. Authors suggested that main loss mechanisms were cell performance, optical interception, optical losses and tracking accuracy.

Other authors prefer to have thermochemical reactions instead of heat storage for the thermal receiver. Zhu et al. (2019) designed, simulated and implemented a hybrid solar photovoltaic and thermochemical parabolic concentrator system, using methanol in the thermal reactor, and water to cool the secondary receiver with PV cells. The concentration ratio was 56x, the wavelength band reflected in PV cells is 500-700 nm, while the rest was transmitted to the thermochemical process that used an internal combustion engine to produce electricity. Results presented an electrical efficiency of the whole system of 35% in the model, while the experimental results reached 31% in an operation temperature of 265 °C. PV cells efficiency was reported as 24% experimentally based on the wavelength band reflected sunlight. However, a standalone presentation of each receiver's efficiencies is not presented, making it difficult to notice the individual efficiency of each component in the system. Similarly, Xing et al. (2022) developed a concentrating photovoltaic (monocrystalline) and solar syngas collector, capable of producing 2 kW of electrical power, with a net solar-to-electricity efficiency of 20.2%, getting a 5.2% higher efficiency compared to using it as a photovoltaic concentrator. Reflected radiation to PV cells was in the range of 600-900nm. The rest was directed to a thermochemical reaction tube, that later was processed to produce more electricity. A sun simulator was used for testing, knowing that xenon lamps cannot generate the same spectra as the sun, but the distribution is similar. The system outperforms each system individually in terms of efficiency when irradiation intensity is as high as 333 W/m^2 (PV concentrator and concentrated solar thermochemistry). A combined non-concentrated and concentrated PV cells receiver allows for a comparison in temperature and produced power. Xian et al. (2021) performed a similar test bench with a hybrid system of PV and methanol decomposition reaction that produced 1532 W of solar power and a solar efficiency of 26.4% at 602 W/m^2. A selective filter was used (NbO_3/TiO_2) to allocate only the wavelength band 600-900nm in PV cells, accounting for more than half of the base efficiency of the cells, representing only 35.2% of sun´s full spectrum.

Liu et al. (2018) applied spectral splitting for agrivoltaics applications, building a PTC with a parabola made of a curved glass coated with a combination of films with different refraction index to obtain a spectral response with the following characteristics. Part of the visible reflected radiation is concentrated on the PV module, while a range of wavelengths near to red and blue (needed for the photosynthesis) are transmitted to the plants. PV module efficiency was 6.8%, while plants were taller and bulkier due to the decrease in temperature in the surface of 2-4 °C, and 26% less evaporation of water (compared to plants without spectral filters). Following the same research line, Zhang et al. (2023) also built a PTC made of dichroic filter, concentrating reflected rays on a PV module, and transmitting the rest to plants, achieving a PV electrical efficiency of 9.9%.

A few other authors also have done similar research on SBS in CPVT but applying liquid filters, where the fluid intercepts a part of sun spectrum, transmitting the rest to PV cells.

Stanley et al. (2016) built a CPVT collector with a liquid filter of propylene glycol and Semiconductor-Doped Glass (HB700), where the PV cells were cooled separately with water. Transmitted wavelength band was between 700-1100 nm for PV cells, while the rest was absorbed by the filter. Some problems affected the performance of the CPVT such as cell shading due to the manufacturing optics of the filter, thus exacerbating the final electrical efficiency. Also, flow boiling due to the propylene glycol boiling temperature was present and data was eliminated from the results. Electrical efficiency achieved was 3.6%, and an overall system efficiency of 50%, with a thermal receiver output of 120 °C.

Otanicar et al. (2018) developed a CPVT collector test bench, using nanofluids dispersed in Duratherm S as fluid filter, increasing the output up to 100 °C. PV cells were cool with DowFrost Propylene Glycol. Nanofluid were gold nanospheres and indium tin oxide nanocrystals, transmitting 59% of the wavelength band 600-1150 nm, and only 85% of the remaining wavelength bands. Thermal efficiency for nanofluid channel reached a maximum of 61% with no flow in the circuit, while PV cells receiver achieved a 5% electrical efficiency based on full sun´s spectrum. Thermal efficiency decreased to ~40% when average temperature in the receiver was operated >110°C. No thermal efficiency for the PV cells receiver was reported.

From the literature review, it is concluded that there are few experimental works of applications of SBS filters in CPVT collectors. Liquid filters are still under development and solid filters can be quite expensive and difficult to manufacture due to the optical specifications that depend on the electromagnetic range of response of the PV cells. To the best of the authors knowledge, there is a literature lack of a LCPVT collector applying SBS, where thermal and electrical efficiency is well documented by presenting PV cells behaviour under load in external conditions with values over 700 W/m^2 for DNI and ambient temperatures ~30 °C. This work is contemplated as a preliminary step to a more robust comparison of multiple filters and a more optimized design of the concentrator with more elevated temperatures in the working fluid and higher electrical efficiency.

Figure 1 presents the basic concept on how spectral splitting works when applying a solid filter, taking as reference the collector geometry from this study. Spectral splitting increases the overall efficiency of the solar panel by redirecting "non-useful" energy for PV cells (due to the non-uniformity of spectral response) to a thermal medium that can absorbe it better, while maintaining the possibility of a decoupled high temperature output. Based in this configuration, in this work is proposed to investigate the thermal and electrical characterization of a low-concentrating photovoltaic thermal collector LCPVT that implements a spectral splitting using a commercially available filter, providing insights on the possibility of reducing the temperature of photovoltaic cells, decoupling high temperatures from the primary receiver, and characterizing its thermal and electrical efficiency.

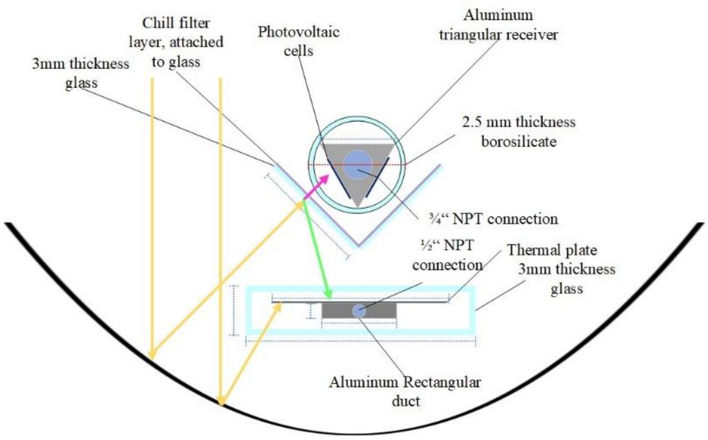

Figure 1. Spectral beam splitting concept applied on the hybrid LCPV/T.

2. Methodology

The hybrid LCPV/T solar collector with the SBS filter is installed and evaluated in Monterrey, Mexico, (lat.: 25.6° North, long.: 100.3° West). Monterrey has a semi-arid climate with a modest elevation of 540 m, being one the warmest major cities in Mexico (BSh Köppen Climate Classification). The solar collector system consists of a test bench where it is evaluated the parabolic concentrator with a hybrid receiver made of aluminum with a duct of triangular shape with 40 photovoltaic cells attached to the two sides that receive the concentrated radiation. The test bench can measure the required variables to characterize the receiver thermal and electrically. This collector has a North-South orientation with an automatic solar tracking system. A V-shaped spectral filter (3M Chill) and a flat shape secondary thermal absorber (RUST-Oleum high heat black paint) where implemented in the hybrid LCPV/T collector as shown in Figure 1. The spectral filter was selected to allow only the transmission of some parts of the radiation from the solar spectrum (part of UV, visible and IR) to the PV cells that are cooled with a fluid (water) that circulates by the triangular receiver. The rest of the spectrum radiation (UV and IR) is reflected in a secondary thermal absorber where the water that circulates in the rectangular duct can be heated to higher temperatures. The fluid that exits the primary receiver is divided into two branches; one connected to the secondary absorber and the other to the main circuit. The mass flow in the thermal absorber can be controlled independently and the temperatures at the inlet and outlet were measured with PT1000 probes.

The LCPVT (without the SBS configuration) with a concentration ratio of 14 was evaluated previously technically and economically by Acosta-Pazmiño et al. (2022), suggesting the change of simple cylindrical thermal receivers of a PTC by hybrid triangular receivers obtaining a payback time of less than 5 years and a 92% higher specific energy yield. Following the idea of adding components to the already installed plants of solar collectors, the proposed configuration of SBS filters presents a simple design where commercially available filters and a secondary thermal absorber can be attached to an LCPVT to reach higher temperatures of the fluid with the potential to develop a SBS filter for mass production.

The optical characteristics added to the spectral response of the PV cells and high temperatures shape the electrical efficiency of the collector (ignoring the emittance of the PV cells due to a special coating applied by the supplier). Literature presents different ways of calculating electrical efficiency (full spectrum, partial spectrum received by PV cells, and efficiency according to temperature), however, it was preferred to use the full spectrum in this case as it is the simplest and clearest option.

The SBS filter was manufactured by applying a 3M chill filter to one side of the glass plate. The thermal receiver was placed inside a rectangular glass channel to reduce the convective heat losses to the ambient. Figure 2 presents the transmittance profile of the 3M chill filter and the glass used for the filter, and for the cover of thermal absorber. The glass has a transmittance above 80% in most parts of the spectrum (300-2700 nm). The 3M chill reduces considerably the transmissivity of the solar radiation in some range of the UV radiation and in less proportion in the far IR. Although this type of filter is not the best configuration to obtain a high response of the monocrystalline PV cells with an effective spectral range of 310-1180 nm (Abdelrazik (2023)), this works is a first approach to investigate the incorporation of commercial filters, having in sight other configurations such as exchanging the receivers' positions and using other commercially available filters, leaving it as future work.

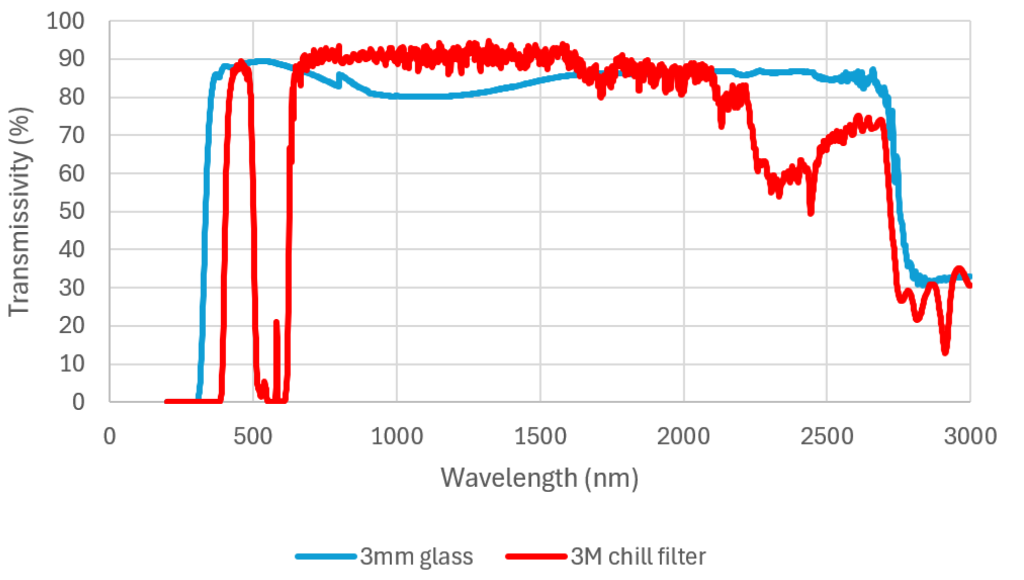

Figure 2. 3M Chill filter and 3 mm glass spectral transmissivity.

Figure 3 shows the LCPVT with the installed SBS filter and the secondary thermal absorber. As a preliminary characterization, it was decided to run experiments at 3 different temperatures: 35, 46, and 55°C, applying a steady-state methodology, recording data points at a rate of one per second. For these experiments (Test 1), thermal (both PVT receiver and thermal absorber) and electrical characteristic curves were obtained. Also, a second set of experiments (Test 2) was run with the secondary thermal absorber uninstalled (only PVT receiver and SBS filter), and increasing gradually the PVT receiver input from 35 to 75 °C to assess impact of the spectral filter in electrical efficiency. Lastly, another unique simple experiment (Test 3) was run to assess the capability of the collector to reduce the flow rate in the input of the secondary receiver, so the output could increase drastically its temperature in comparison to the primary aluminum triangular receiver.

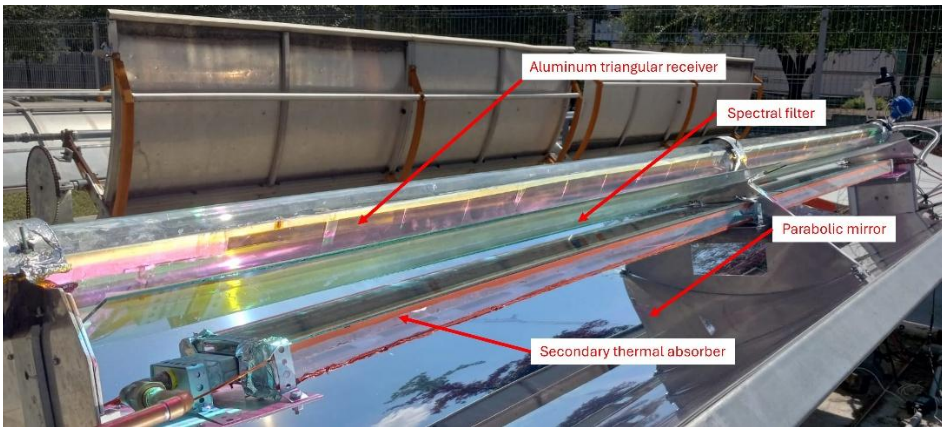

Figure 3. Hybrid low-concentrating Photovoltaic/Thermal collector with spectral filters and a secondary thermal absorber.

3. Results

Experiments of Test 1 were performed during the months of October 2024 and September 2025. Inlet and outlet temperatures were kept stable, having a difference of temperature in the first receiver ranging between 0.66 and 0.98°C as the collector temperature decreased while efficiency increased. Flowrate ranged from 0.12 to 0.19 l/s, and average weather conditions were 800 W/m^2 for direct normal irradiance, 30 °C for ambient temperature, and 1 m/s for wind speed. Figure 4 shows the experimental thermal characteristics curves of efficiency versus reduced temperature of the PVT receiver and the secondary thermal absorber. The reduced temperature is defined as the difference between the mean temperature of the fluid T_m and the ambient temperature T_a, divided by the direct normal incident irradiance (DNI) on the aperture area of the solar collector. These characteristic curves were obtained from one-minute average data points collected through different testing temperatures. The total thermal efficiency of the CPVT with the configuration of the SBS filter with thermal absorber was 45%, where 27% correspond to the PVT receiver and 18% to the secondary thermal absorber. Tendencies (thermal coefficients) may be seen as preliminary, as there are a lack of data points and a narrow range of tested temperatures for all the curves. However, it can be observed that thermal efficiency decreases with the increase of the reduced temperature as expected due to the higher convective heat losses to the ambient. The characteristic curve of the electrical efficiency of the PV cells shows a lineal decrease with the reduced temperature reaching a maximum electrical efficiency of 2.7%. For this prototype of SBS filter and secondary thermal receiver, the following optical losses were presented. First, imperfections of the parabolic mirror made of anodized aluminum (90% reflectance). Second, reflected rays are transmitted and reflected by the spectral filter. Third, transmitted rays are reduced by 80% due to the glass where the filter is attached, while reducing it by 90% due to the borosilicate cover in the hybrid triangular receiver. Finally, the reflected spectrum from the filter is reduced by 80% by the glass of the filter, and 80% more due to the thermal absorber glass cover.

In Test 2, experiments were conducted in September of 2024 to evaluate only the effect of the SBS filter alone in the electrical performance of the CPVT. Flowrate ranged from 0.27 to 0.33 l/s, and average weather conditions were 793 W/m^2 for direct normal irradiance, 31 °C for ambient temperature, and 0.7 m/s for wind speed. For this configuration (without the secondary thermal absorber), the temperatures of the PV cells versus the reduced temperature (Tm-Ta) of the PV panel are shown in Figure 5 for the experiments with and without the SBS filter. The surface temperature of the PV cells was reduced by 10 °C when the SBS filter was used, however there was a decrease in the electrical efficiency. The electrical efficiency of the CPVT without SBS filter was 7.3 % while the efficiency of the CPVT with the SBS filter (without thermal absorber) was 5%. This reduction of efficiency can be attributed to the low transmissivity of the glass used to build the filter and the transmissivity band of the spectral filter (Figure 2) that is not the most appropriated for the electrical response of the PV cells employed.

Test 3 was performed to show the potential of the configuration of SBS filter and secondary thermal absorber to separate the heat of low temperature of the hybrid receiver from the heat of medium or high temperatures of the thermal absorber, without affecting the electrical efficiency. For this test, an experiment in the CPVT with the SBS configuration proposed was run for a lower flow rate of 0.003 l/s, maintaining the primary receiver at 33°C average temperature. An average temperature of 47° C at the exit of the secondary thermal absorber was reached. This output temperature of the CPVT with the proposed configuration of SBS filter can be increased to higher temperature reducing the mass flow in the thermal absorber, while the fluid at the exit of the PVT receiver can be used as a preheating fluid for the secondary receiver.

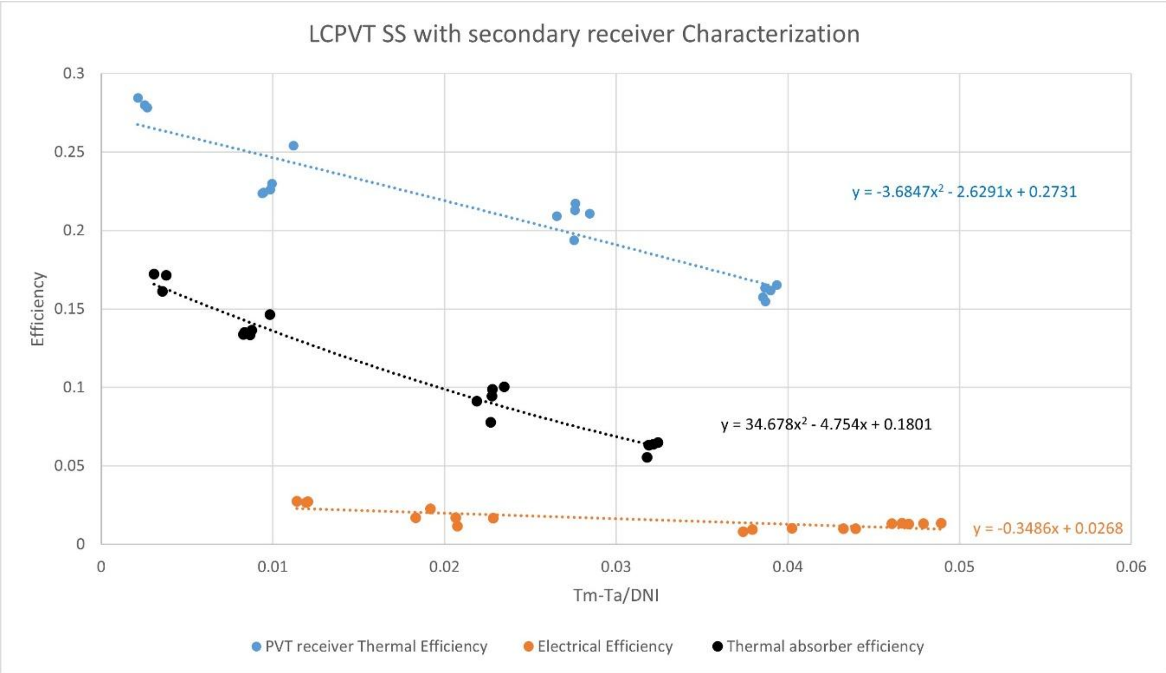

Figure 4. Thermal and electrical efficiency of the LCPV/T with SBS filter and secondary thermal absorber.

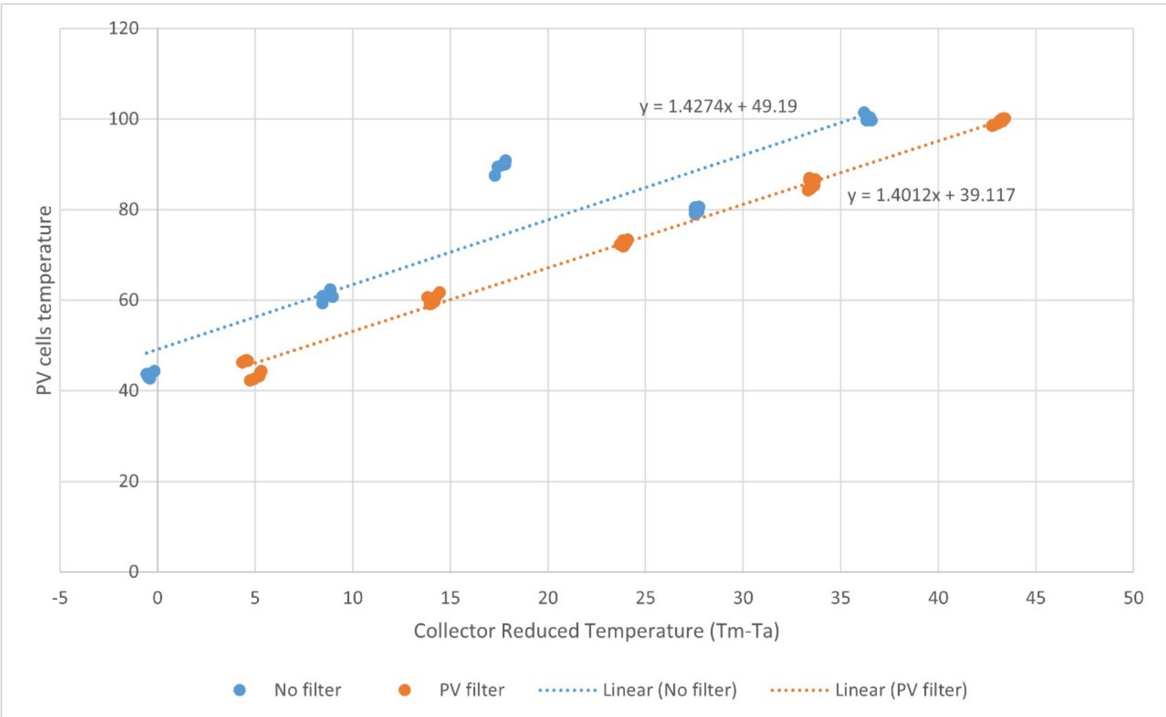

Figure 5. PV cells in hybrid triangular receiver temperature tendency with and without SBS filter.

4. Conclusions

The effect on the efficiencies and PV temperatures of a CPVT collector due to the implementation of a solid SBS filter with a secondary thermal absorber was experimentally investigated. The following conclusions can be drawn from the experimental results. The SBS made of glass with a layer of commercial filter showed to reduce the temperature of the PV cells of the PVT receiver up to 10°C with respect to a receiver without the filter. A total thermal efficiency of 45% of the CPVT with the SBS filter and the thermal receiver was achieved. However, the electrical efficiency of the PV cells of the CPVT was reduced from 7.3 % without the SBS and the thermal receiver to 2.7 % for the SBS configuration proposed. The low efficiency obtained might be attributed by optical losses due to the reflection and reduction of transmissivity by the glass of the filter, blockage of the secondary thermal absorber and not the appropriate filtering of the solar spectrum by the SBS developed. Although a poor performance was obtained for this preliminary design of filter, the SBS made of a commercial filter layer and secondary thermal receiver proved the technical feasibility of generating heat of higher temperature reducing the surface temperature of the PV cells. As a future work, the following modifications will be explored. Selection of different type of films for the SBS to have a better spectral selection of the solar radiation that matches the response of the PV cells, switching the primary and secondary receivers and a redesigning of the thermal absorber to enhance the absorption of solar radiation and to reduce the blockage of radiation to the PVT receiver.

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