

Experimental evaluation of a prototype hybrid CPV/T system utilizing a nanoparticle fluid absorber at elevated temperatures



Todd Otanicar^{a,*}, John Dale^a, Matthew Orosz^a, Nick Brekke^a, Drew DeJarnette^a, Ebrima Tunkara^b, Kenneth Roberts^b, Parameswar Harikumar^c

^a Department of Mechanical Engineering, The University of Tulsa, Tulsa, OK 74104, USA

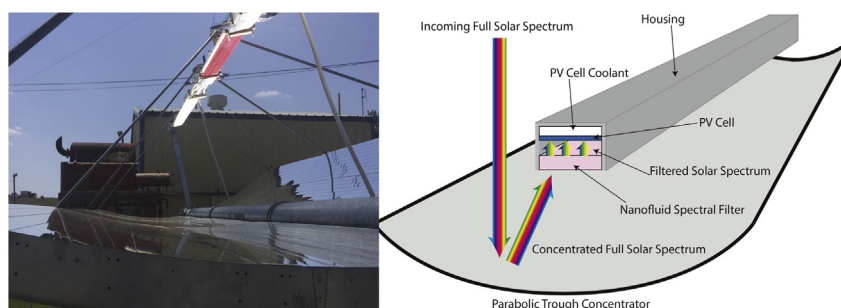
^b Department of Chemistry, The University of Tulsa, Tulsa, OK 74104, USA

^c Department of Physics, The University of Tulsa, Tulsa, OK 74104, USA

HIGHLIGHTS

- Experimental demonstration of hybrid CPV/T collector operating over 100 °C using nanoparticle filter with flowing fluid.
- Nanoparticle filter utilizes UV/Visible absorption with gold particles and infrared absorption with ITO.
- Thermal and electrical efficiency of 61% and 4% respectively at 110 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

Novel approaches for solar energy conversion continue to garner interest as a potential thermal and electrical energy source. Additionally, the need for systems capable of producing thermal energy at temperatures up to 300 °C is growing as a means to provide process heat to industry and distributed generation for small communities. An approach that has seen recent increased interest is the hybrid concentrating photovoltaic/thermal collector that can co-produce electricity and heat energy above 100 °C. One technique for this is to use nanoparticles in the heat transfer fluid to spectrally filter off wavelengths poorly utilized by the photovoltaic component. Here, we have demonstrated the first on-sun operation of a nanoparticle based hybrid CPV/T solar collector at temperatures exceeding 100 °C using a combination of gold and indium tin oxide nanoparticles in Duratherm S flowing in the receiver, with an aperture area a full order of magnitude larger than other tests. At 14× concentration the system achieved a photovoltaic efficiency of 4% while achieving a peak thermal efficiency of 61% with an outlet temperature of the fluid of 110 °C.

1. Introduction

Conventional single junction photovoltaic (PV) cells only convert a fraction of the full solar spectrum to electricity leading to a large portion of the incoming sunlight being reflected or thermalized. Despite

the limited ability to use the full solar spectrum, PV continues to decrease in cost and increase in worldwide installation. Unfortunately, the cost of batteries makes energy storage cost prohibitive particularly at industrial and utility scales. Conventional thermal absorbers, such as those used in flat plate solar collectors or parabolic troughs (CSP), are

* Corresponding author.

E-mail address: todd-otanicar@utulsa.edu (T. Otanicar).

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highly efficient at capturing solar energy through the full solar spectrum and the thermal energy is readily stored at much lower costs as thermal energy. CSP type systems in particular though are significantly more costly than their PV counterpart, neglecting any significant pricing premium on dispatchability [1]. Because of the dispatchability of thermal energy and the low cost of PV systems there has been significant recent effort at hybridizing the two systems. One of the primary challenges is the competing thermal nature of the two systems; PV is most efficient at low temperatures and CSP when used for electrical power production increases in efficiency with temperature. Hybrid systems that are going to operate at higher temperatures, as required by process heat needs or for electricity production, will need to have novel optical and thermal designs such that the PV and thermal system are uncoupled or weakly coupled, through some form of spectral splitting. An overview of spectral splitting technologies can be found in the recent review by Mojiri et al. [2], and details of hybrid CPV/T systems are in extensive detail by Ju et al. [3]. Recently, Widyolar et al. compiled a comprehensive analysis of single and two stage CPV/T designs using silicon and gallium arsenide cell technologies and highlights some of the key technoeconomic challenges facing CPV/T systems particularly as they relate to electrical power production [4]. Below we focus on reviewing experimental CPV/T work in the literature.

Early experimental work focused on CPV/T receivers where thermal energy is waste heat removed from the PV cell. One such application was by Coventry et al. who used a parabolic trough to concentrate ($37\times$ geometric, and $30\times$ PV) light onto a Si PV cell receiver [5] where waste heat was recovered via a water-glycol flow loop embedded in the back of the receiver. The system achieved a net efficiency of 69%, with the PV and thermal components operating at 11% and 58% efficiency respectively with the thermal fluid reaching temperatures less than 80°C [6]. While this work demonstrated a CPV/T system, the working thermal fluid limits uses for low temperature heating applications and no spectral splitting was employed.

CPV/T systems that achieve much higher working fluid temperatures are well studied numerically [7–9], but limited applications at higher temperatures have been experimentally tested. Additionally, the number of experimental CPV/T systems that employ spectral splitting are fairly limited. Below, we review experimental tests of systems employing spectral splitting and filtration.

Kandilli proposed and tested a hybrid system using a parabolic dish that focused solar energy onto a “hot mirror” which transmitted selected wavelengths to a silicon PV cell while reflecting the remaining to a conventional CSP tube mounted to the side of the dish [10]. In this application maximum fluid outlet temperatures reported were 55°C . The system, comprised of three dishes, resulted in a thermal power of 141 W and electrical power output from the cells of 18.4 W. Solar thermal and PV cell efficiency were not directly reported.

Widyolar et al. investigated a hybrid PVT system that incorporates a set of PV secondary mirrors at the focal point of a parabolic trough concentrator that reflect a portion of the solar spectrum back onto a traditional thermal absorber allowing the system to co-produce electricity and thermal fluid at $\sim 365^\circ\text{C}$ under $\sim 60\times$ geometric concentration ratio [11]. The secondary PV mirror is made from GaAs PV cells attached to an aluminum extrusion that is actively cooled, instead of use a dichroic material the mirror effect relies on GaAs natural band gap cut off of 870 nm to reflect approximately 92% of the low energy light back to the thermal receiver, this entire system is installed in an evacuated glass cylinder [11]. Peak thermal efficiency is reported as roughly 37%, with the fluid inlet and exit temperatures around 310°C and 350°C respectively. A proper vacuum could not be achieved in the receiver due to complications with incorporating the PV receiver, so reported thermal performance was adjusted, assuming a properly evacuated receiver. The maximum PV performance was 8% although the reported PV efficiency of 8% does not correspond to the thermal results as it was taken from a partly cloudy day under substantially reduced flux.

Xu et al. proposed and modeled the performance of a hybrid PVT system based around a triple junction AlGaInP/LnAlGaAs/GaAs PV cell, encapsulated between sapphire plates, deployed at the focal point of a dual axis tracking dish concentrator [12]. The triple junction cell efficiently converts as much of the visible and UV spectrum as possible, while transmitting approximately 75% of the out-of-band (mostly IR) light to a thermal absorber. The concentrated flux intensity is non-uniformly distributed across the PV cells, increase sing from ~ 50 to $580\times$, from the outer edge to the center of the PV cells. Passive cooling with aluminum fins and active cooling with embedded water channels were considered and predicted average cell temperatures of 87°C and 67°C respectively. The cell module efficiency is reported as a function of in-band photon energy and was predicted to be 48.2% and 49.1% for the passive and actively cooled conditions respectively. Thermal efficiency of the proposed hybrid PVT system was not considered or reported.

Another approach that uses selective absorption, achieved with a thin film absorbing filter was demonstrated by Stanley et al. [13]. In this approach a semiconductor doped glass is embedded within a transparent glass tube that contains the working heat transfer fluid (propylene glycol) absorbing below 700 nm and above 1100 nm. The system employed a parabolic trough concentrator that provided $42\times$ geometric concentration ratio. PV cells were Sunpower Maxxeon cells connected in series. During the experimental tests the observed PV efficiency was 3.6–4.0%, while the observed thermal efficiency was $\sim 35\%$ at working fluid temperatures of 120°C , approaching the maximum working temperature due to onset of flow boiling. The authors note that the addition on vacuum insulation around the primary absorber tube could lead to enhanced efficiency.

The volumetric approach outlined above by Stanley et al. [13,14] is a novel approach for volumetric selectively using a glass insert, while a number of others have proposed volumetric selective absorbers using nanoparticles [7,15–18]. The vast majority of the nanoparticle based CPV/T arrangements have been numerical studies [17,19], focused on the design of the optical filters [7,15,20], including nanoparticle characterization, thermal packaging, and system design [9,21–23]. Using a volumetric approach has some advantages over dielectric surfaces that reflect light onto flat surfaces for absorption. First, there exists a heat transfer advantage by directly absorbing light in the fluid versus absorbing on a surface followed by subsequent convection. Second, the use of ultra-small particles such as nanoparticles effectively eliminates any angle of incidence optical losses in the thermal absorber. For dielectric surfaces not only does the bandedge change but also optical losses can be exaggerated at non-normal angles of incidence. Below we outline the limited number of on-sun experimental work for nanoparticle CPV/T types of systems.

Spectral filtration using a nanoparticle fluid filter has been experimentally demonstrated by Crisostomo et al. [24]. The hybrid CPV/T system reported employs a linear Fresnel lens to focus ($8.3\times$ & $16.6\times$, thermal and PV area-based concentration ratios respectively) light onto a Si PV module. The spectral filter/thermal receiver is a glass tube situated directly in front of the PV module. The PV module is not actively cooled in the arrangement tested so all thermal gains are the result of the nanofluid absorber. Varying concentrations of silver nanodiscs in water were pumped through the thermal receiver. Notably, the particles used here are primarily absorbing in the visible spectrum. A maximum temperature of 70°C was obtained during the on-sun experimental testing. Thermal and PV efficiencies are not reported individually, but a peak overall efficiency of 33.2% was obtained, a significant improvement over pure water. The authors also experimentally demonstrated the thermal decoupling between the nanoparticle based fluid absorber and the PV cell over the range of temperatures tested ($35\text{--}55^\circ\text{C}$ mean fluid temperature) [24].

An et al. experimentally investigated a fluid based spectral filter for CPV/T systems based on polypyrrole [25]. The experimental system consisted of a linear Fresnel lens concentrating ($10.2\times$) light onto a

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