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Hybrid Solar Collector Using Nonimaging Optics and Photovoltaic Components

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ABSTRACT

The project team of University of California at Merced (UC-M), Gas Technology Institute, and Dr. Eli Yablonovitch of University of California at Berkeley developed a novel hybrid concentrated solar photovoltaic thermal (PV/T) collector using nonimaging optics and world record single-junction Gallium arsenide (GaAs) PV components integrated with particle laden gas as thermal transfer and storage media, to simultaneously generate electricity and high temperature dispatchable heat. The collector transforms a parabolic trough, commonly used in CSP plants, into an integrated spectrum-splitting device. This places a spectrum-sensitive topping element on a secondary reflector that is registered to the thermal collection loop. The secondary reflector transmits higher energy photons for PV topping while diverting the remaining lower energy photons to the thermal media, achieving temperatures of around 400°C even under partial utilization of the solar spectrum. The collector uses the spectral selectivity property of Gallium arsenide (GaAs) cells to maximize the exergy output of the system, resulting in an estimated exergy efficiency of 48%. The thermal media is composed of fine particles of high melting point material in an inert gas that increases heat transfer and effectively stores excess heat in hot particles for later on-demand use.

Keywords: Hybrid photovoltaic thermal system, solar PVT collector, nonimaging optics, GaAs, solar energy, combined heat and power

1. INTRODUCTION

The hybrid photovoltaic thermal (PV/T) system use combined photovoltaic (PV) device and solar thermal collector to produce both heat and electricity. A significant amount of research and development work on the PV/T technology has been done since the 1970s as extensively reviewed in [1]-[2]. Mostly, the heat transfer fluid used in these technologies is generally air or low pressure water because these designs are limited to relatively low temperatures due to the decrease in solar cell efficiency with rising temperature. The conventional hybrid PV/Ts have designs to use a heat transfer mechanism that is directly attached to the silicon PV cells. Crystalline indirect bandgap solar cells such as mono- or multi-crystalline silicon cells typically are affected much more negatively by raising their working temperatures compared to the direct bandgap, thin film PVs [3]-[4].

In this study, a novel hybrid concentrated PV/T is proposed, the collector transforms a parabolic trough, commonly used in concentrated solar power (CSP) plants, into an integrated spectrum-splitting device. This places a spectrum-sensitive topping element on a secondary reflector that is registered to the thermal collection loop. The secondary reflector transmits higher energy photons for PV topping while diverting the remaining lower energy photons to the thermal

media, achieving temperatures of around 400°C even under partial utilization of the solar spectrum. It uses the spectral selectivity property of the world record single-junction gallium arsenide (GaAs) cells, manufactured by Alta Devices, to maximize the exergy output of the system.

2. PV/T SYSTEM DESIGN

The main components of the proposed system are shown in Figures 1 and 2. The parabolic mirror with a 5 m² aperture area and 45° rim angle is the primary reflector, which reflects and focuses incoming direct beam solar irradiance toward the hybrid PV/T receiver. The design of the PV/T receiver consists of: (1) the world record single-junction gallium arsenide (GaAs) PV cells from Alta Devices manufacturer, which mounted directly over the aluminum minichannels. The purpose of these minichannels struts is to serve as a fluid channels to provide active cooling to the GaAs cells. (2) Curved mirrors which approximate the involute portion of the compound parabolic concentrator (CPC) where flat minichannels cannot, (3) selectively coated high temperature counter-flow absorber which receives concentrated light from the CPC and serves as the high temperature (500°C) fluid channel, (4) outer glass tube which allows the entire receiver to be evacuated.

Light that strikes the GaAs cells is spectrally split based on the band gap cutoff (870 nm). About 90% of wavelengths below this band gap being absorbed and converted to electricity or heat, and about 92% of the wavelengths above the band gap being reflected towards the high temperature absorber (see Figure 3). Thus the system produces electricity directly and low grade heat is generated by actively cooling the cells via the minichannel substrate. The high temperature absorber receives the spectrally split light reflected from the GaAs cells as well as reflected light from the curved mirror involute portion of the CPC and light that strikes the absorber from the primary parabolic mirror directly. The high temperature tube receiver, working under the concentration ratio up to 60X and can achieve 500°C under vacuum.

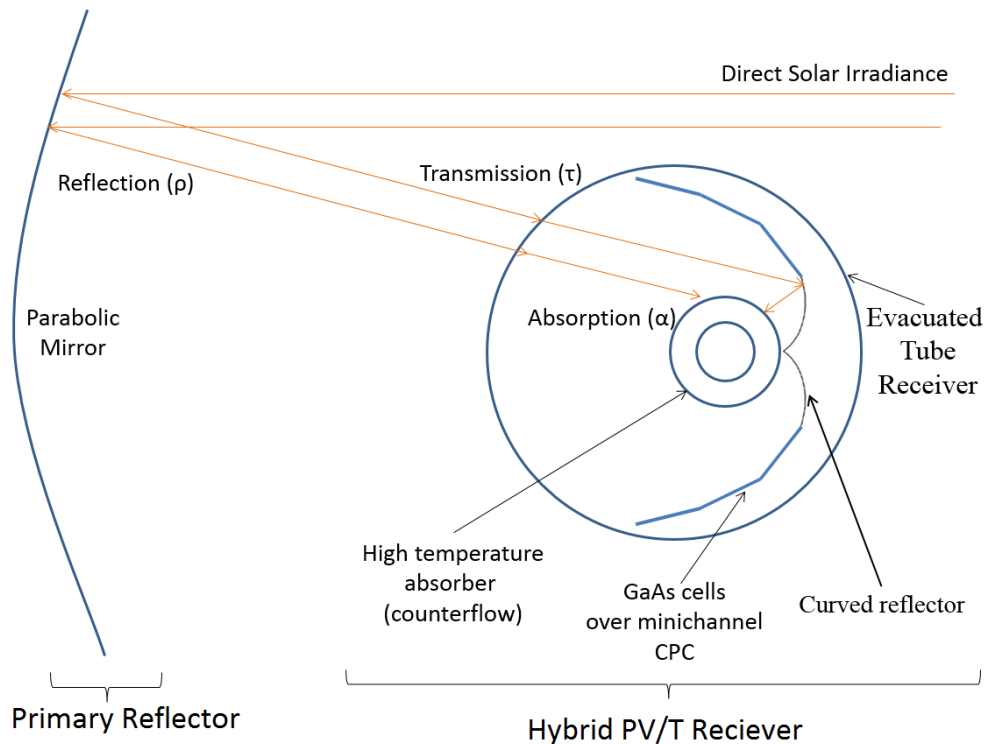


Figure 1. PV/T collector components

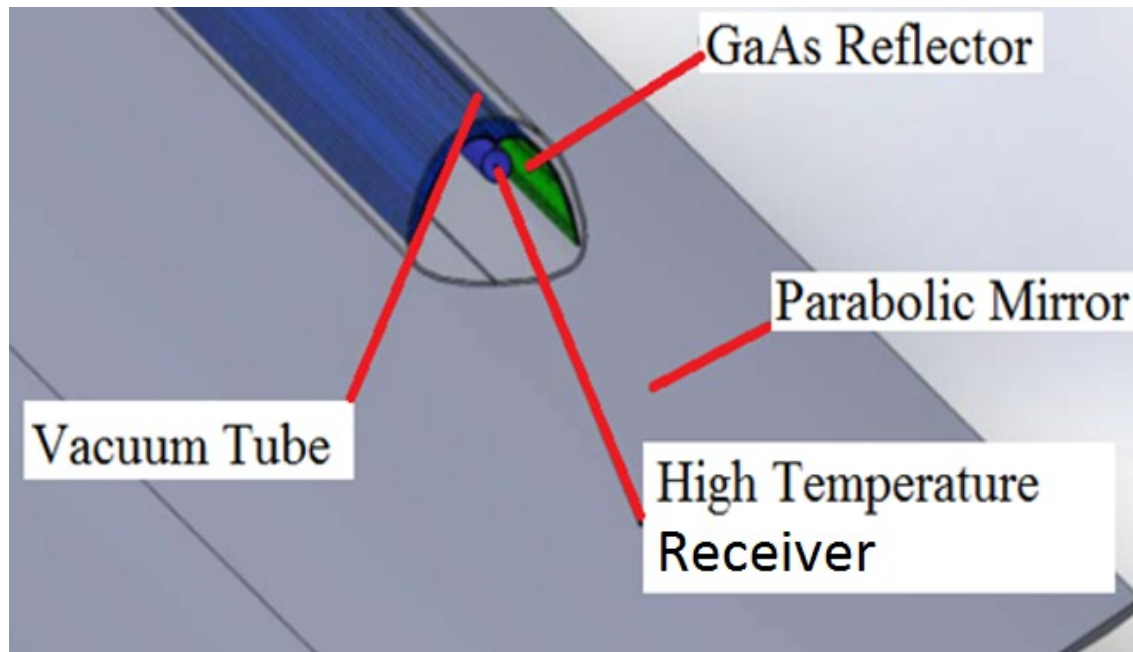


Figure 2. Hybrid PV/T receiver

The design of the hybrid PV/T receiver is based on previous work on inserted internal CPC reflectors and metal glass seals [5]-[6]. Standard parabolic troughs use a 70 mm diameter absorber [7], however, the angular potential of the surface is not fully utilized. This is effectively wasted real-estate and a standard parabolic trough system focusing from 5 m to a 70 mm diameter tube will only reach concentration ratios ~ 23X. This problem is solved using a secondary concentrator as the CPC illuminates the entire surface of a much smaller diameter absorber and in our case achieves a geometric concentration ratio of approximately 60X which allows it to operate at similar temperatures as conventional parabolic trough systems (and higher) even under partial utilization of the solar spectrum.

The concentration ratio from Parabola to CPC = $5000\text{mm}/111.12\text{mm} = 44.9$

The concentration ratio from CPC to high temp absorber = $111.12\text{mm} / (\pi * 26.7) = 1.32$

The final system concentration ratio = $5000 / (\pi * 26.7) = 59.6$

AD19631 Reflectivity Data

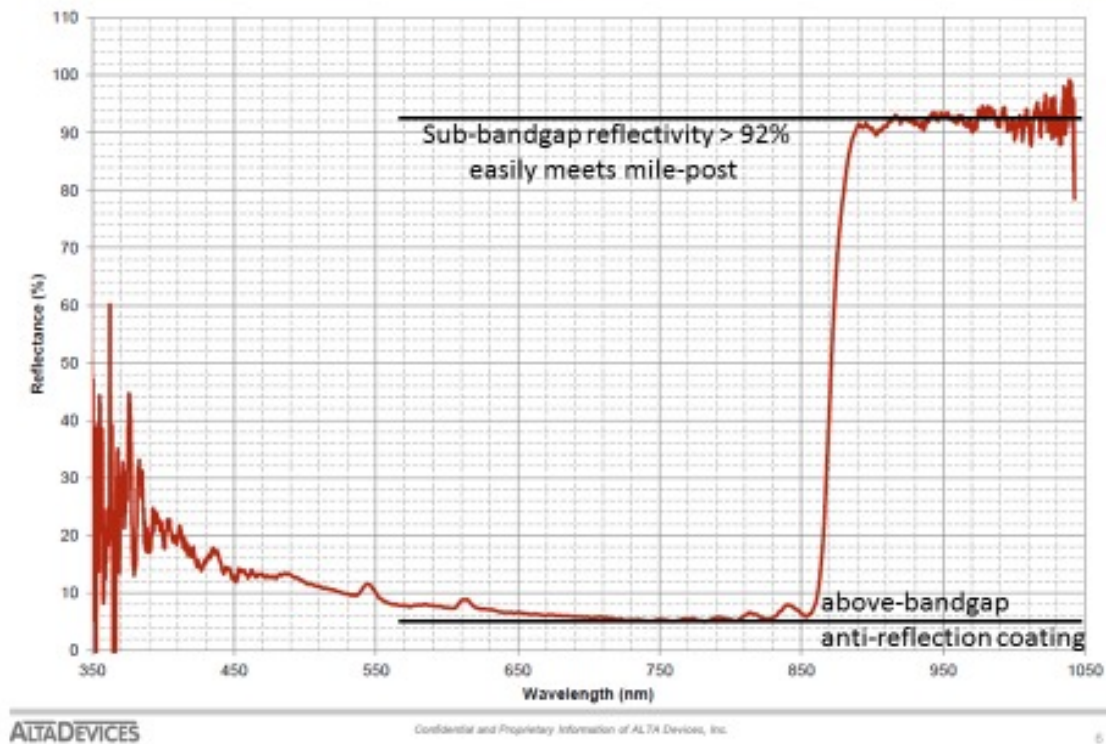


Figure 3. GaAs PV cells manufactured by Alta Devices: reflectance (%) vs. wavelength

The space between the absorber and the glass shell in the receiver tube is evacuated, so that convection and conduction are eliminated, and heat is transferred from the hot absorber to the external glass shell only by radiation. As a result, these collectors are efficient even at high operating temperatures. Within the vacuum the heat sinking of the solar cell will be kept at a relatively low temperature (below 200 Celsius) and therefore have negligible effect on the heat loss.

3. PV/T SYSTEM PROTOTYPE

The experiment was performed at University of California Merced's Castle Research Center. The latitude and longitude for the location is 37.3°N, and 120.6°W, respectively. Figure 4 shows the hybrid PV/T Receiver prototype. Figure 5 shows the hybrid PV/T receiver installed in front of the parabolic mirror. The thermal loop and the testing equipment are shown in figure 6.

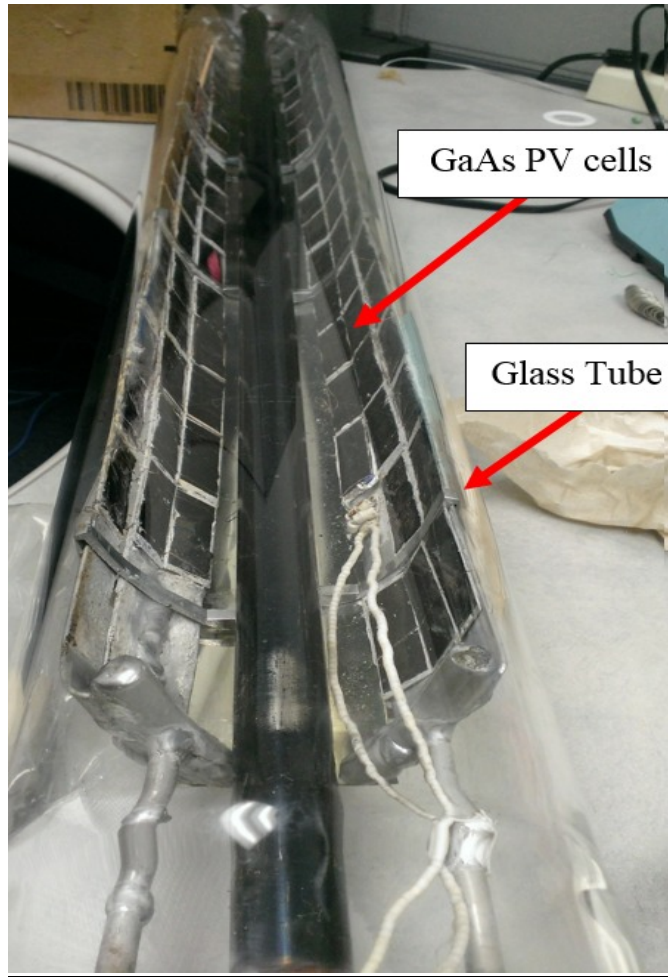


Figure 4_Hybrid PV/T Receiver

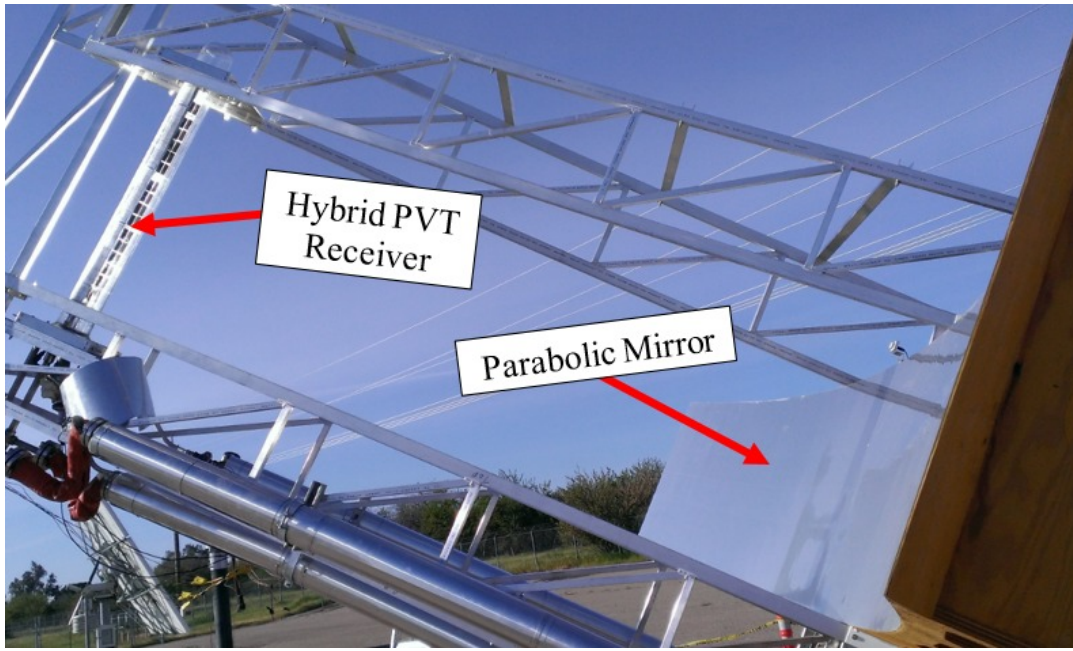


Figure 5. Parabolic Mirror and Hybrid PV/T Receiver

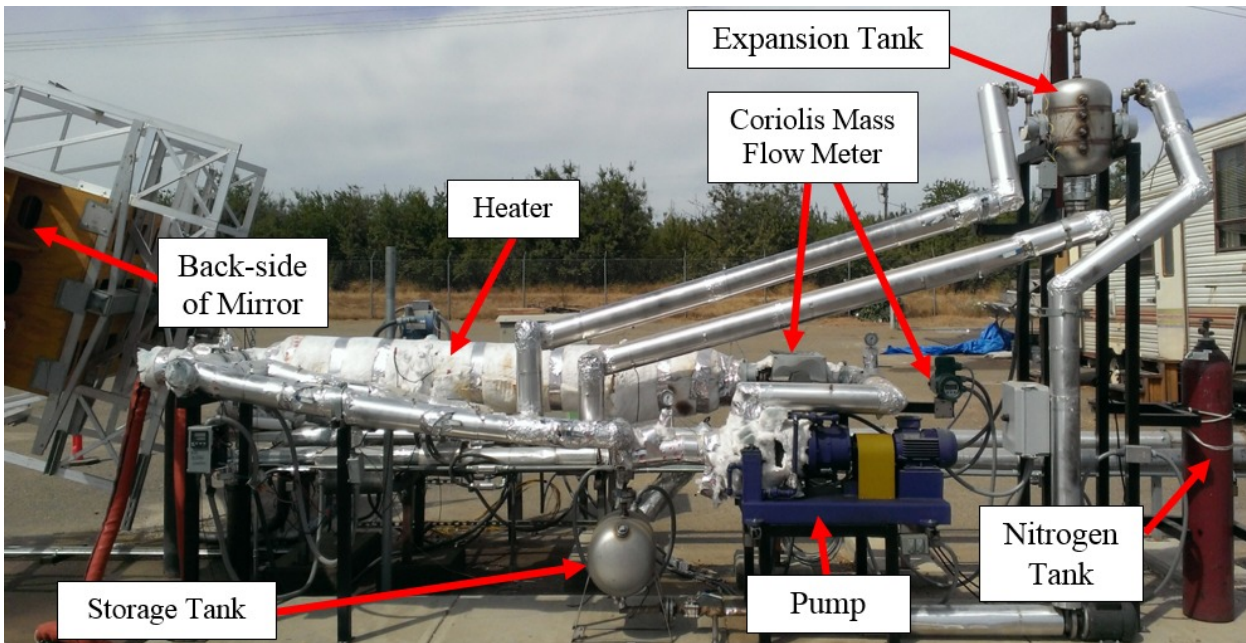


Figure 6: Temperature loop

4. RESULTS AND DISCUSSION

The solar to thermal efficiency versus outlet temperature of fluid stream (T_{out}) of the proposed PV/T is shown in Figure 7. The black dots are the experiment results, while the red line is the predicted efficiency from the model. The maximum temperature the system achieved slightly less than 400 °C and the maximum exergy efficiency around 48%.

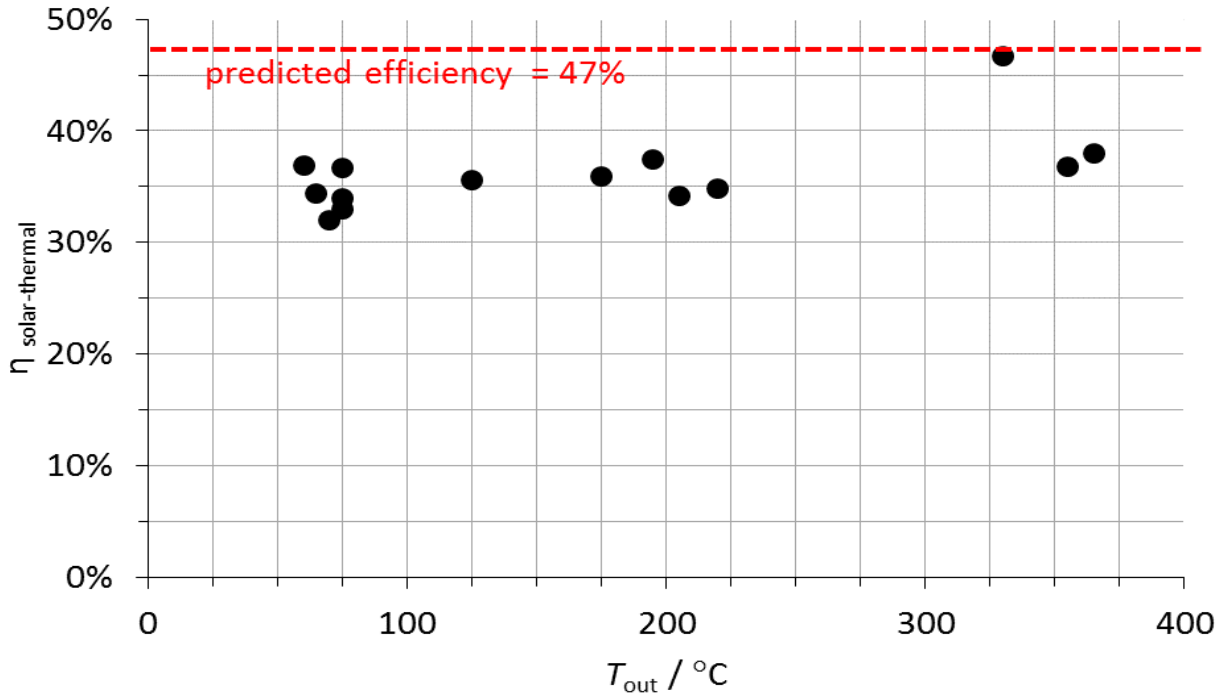


Figure 7: Solar to thermal efficiency

5. CONCLUSION

The project team of University of California at Merced (UC-M), Gas Technology Institute, and Dr. Eli Yablonovitch of University of California at Berkeley developed a novel hybrid concentrated solar photovoltaic thermal (PV/T) collector using nonimaging optics and world record single-junction Gallium arsenide (GaAs) PV components integrated with particle laden gas as thermal transfer and storage media, to simultaneously generate electricity and high temperature dispatchable heat [8]. The collector transforms a parabolic trough an integrated spectrum-splitting device. The collector uses the spectral selectivity property of Gallium arsenide (GaAs) cells to maximize the exergy output of the system. The high temperature tube receiver, working under the concentration ratio up to 60X. The system output an exergy efficiency of 48% and around 400 °C. The thermal media is composed of fine particles of high melting point material in an inert gas that increases heat transfer and effectively stores excess heat in hot particles for later on-demand use.

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