Linear Fresnel Reflector based Solar Radiation Concentrator for Combined Heating and Power

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Abstract. We have designed and realized a test rig to characterize concentrated solar-based CHP (combined heat and power) generator. Cost benefit analysis has been used to compare alternate technologies, which can cogenerate electrical and thermal power. We have summarized the experimental setup and methods to characterize a concentrated solar thermal (CST) unit. In this paper, we demonstrate the performance data of a concentrated solar thermal system.

Keywords: Linear Fresnel reflector, concentrated PV thermal, characterization, solar to thermal efficiency
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INTRODUCTION

There are several ways to generate useful power from solar radiation. The most prevalent methods involve the use of PV cells (flat module), concentrated PV modules, and concentrated solar power (CSP). Concentrating solar radiation can also cogenerate electrical and thermal power, which can lead to very efficient (>70%) renewable power generators. The thermal power can be used for different applications (e.g. hot water/steam generation, cooling, water desalination/distillation, additional electrical power through organic rankine cycle (ORC), etc.). Exergy analysis indicates that hot water/steam generation is the most cost-effective usage of thermal power in locations with high cost of thermal power. Solar-based cogeneration can be installed on rooftops of green commercial buildings with requirement of electrical power and hot water and/or steam (e.g. hotels, hospitals, factories, schools, municipal buildings, etc.). We designed and realized a test rig to characterize concentrated solar-based CHP (combined heat and power) generators. In this paper, we demonstrate the performance data of a concentrated solar thermal unit.

The appropriate energy conversion mode has to be chosen depending on the geographical location, scale of the installation, and government policies/incentives. The following figures of merits need to be considered while choosing the type of solar energy conversion:

- Cost per unit of power ($/Wp)
- Levelized cost of energy (LCoE)
- Payback period (or RoI/IRR/NPV)
- Power per unit area
- Power per unit weight (important only for rooftop installation)

Detailed analysis of the key figure of merits for different solar radiation based power generation technology indicates that for certain specific applications in regions with high DNI, concentrated photovoltaic thermal (CPVT) technology is the optimum solution. In this paper we have provided details of the commercial and geographical application space for CPVT, cost benefit analysis, and outdoor characterization test-rig design. We also outline the experimental setup and methods to characterize a CST unit. The experimental data related to thermal power from CST, system level efficiency, and data analysis methodology have been highlighted here. The results and discussion section analyzes the characterization results collected over a span of 40 hour.

COST MODEL

The motivation of developing a cost benefit analysis model was to compare the performance of CPVT with alternate systems, which can provide combined heating, cooling, and power. Accordingly, we have compared the performance of several cogeneration units. The quality of the thermal energy is one of the most critical parameters in this type of technology comparison. The quality is related to the temperature level of the flow. Thus, we have highlighted the comparison of systems with similar thermal energy quality (i.e. temperature of thermal energy). The performance of CPVT, PV+CST, and bio-gas engines have been compared in this study.

We have developed a parameterized excel based cost model, which provide flexibility of user inputs. This model also assists in doing parametric and sensitivity analysis. The key figures of merits are levelized cost of energy (LCoE) and payback period. We have also considered power per unit area and power per unit weight as important technical metrics.

Cost benefit analysis indicate that CPVT based CHP can be grid competitive without government subsidies. However, end users can get further benefit by availing the following government subsidies for solar renewable technology based product:

- Subsidy on the capital expenditure
- Accelerated depreciation allowance
- Soft loans
- Feed in tariffs
- Carbon credit.

Thus, this technology can provide electrical power and heating at a significantly cheaper rate compared to the grid. The payback period is computed using the following model:

$$\mathrm{Revenue}_{\mathrm{Electrical\,Energy}}\left(\frac{(1+r/100)^{x}-1}{(1+r/100)-1}\right)+\mathrm{Revenue}_{\mathrm{Thermal\,Energy}}\left(\frac{(1+r/100)^{x}-1}{(1+r/100)-1}\right) = Capex\left(1+R/100\times x\right)+Installation \quad (1)$$

Where, r is rate of increase of fuel cost on a yearly basis. R is the rate of O&M cost as a function of capital expenditure, and x is the pay back period. Figure 1a compares the levelized cost of energy (LCoE) of alternate CHP systems. The cost of energy is computed after considering the government subsidies, which are provided by government of India to a profit making organization (30% of capital expenditure).

The second generation cost model will include other government subsidies, which are available to the end customer (e.g. accelerated depreciation, soft loans, peak load benefits, etc.). Figure 1b compares the payback periods of alternate CHP systems with government subsidies. The DNI for all these results (Figure 1) is 1680 kWh/m^2 per year. The cost of the CPVT instrument is 1000 \$/kW (both forms of energy, thermal and electrical, are considered), cost of electrical balance of system is 800 \$/kW, and cost of thermal balance of system is 400 \$/kW. We also considered a case study of 300-bed hospital at a location in India with DNI of 2100 kWh/m^2 per year. Application of 73 CPVT units can reduce the annual energy bill by 25% (approximately \$275K per year).

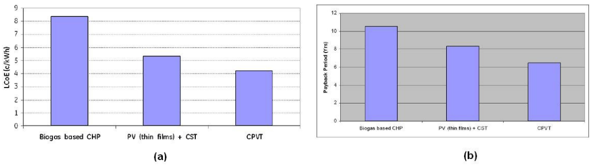

FIGURE 1. (a) Comparison of the cost of energy of the power generated by alternate CHP systems. (b) Comparison of the payback period of alternate CHP systems.

CHARACTERIZATION OF CONCENTRATED SOLAR THERMAL SYSTEM

The characterization test rig of the concentrated solar thermal (CST) unit has been described in this section. The experimental set-up is shown in Figure 2a. The entire system has been installed on a rooftop of a building to ensure minimal shadow effect. The CST unit focuses solar radiation on the channels containing heat transfer fluid (HTF) and hence increases the temperature of water flowing through the channels. The water pressure is maintained using the control unit and can be monitored using the flow meter. The hot water is then passed through the storage tank (with heat exchanger) where thermal power of the hot water through pipes is utilized to heat up the stored water. The characterization test rig can be divided up in 4 sub-systems:

- Thermal BoS
- Electrical subsystems
- Control subsystem
- Civil work for installing the system

The CST unit has one port in each section (A and B, as shown in Figure 2b) and either of them can be used as an inlet port or an outlet port for the liquid to flow in or out of the unit. The liquid (water in the current set-up) comes in through the inlet port and flows through the channels that are placed at the focused zone and leaves the unit through the outlet port. To protect the unit from environmental factors, it is covered by glass whose transmittivity is around 85%. The photovoltaic (PV) cells can be placed just beneath the HTF containing channels, which lead to higher system level efficiency. The elevation angle of the Sun changes over the entire year. To compensate for those effects, the Chromasun unit has been kept on a mounting structure whose elevation can be changed. The mounting structure is aerodynamic and properly secured to the ground, and therefore, has a high wind loading capability. As aluminum has better reflectivity, the CST unit from Chromasum Inc. uses a number of aluminum flat plates whose positions are controlled through microprocessor-based motors.

Two thermocouples are connected to the inlet and outlet port of the CST unit. The thermal power, E_o, generated can be computed as:

$$E_o = \dot{m} C_p \Delta T \qquad (1)$$

where, $\dot{m}$ is the mass flow rate of water flowing through the channels, C_p is the specific heat of the water and ΔT is temperature difference between outlet and inlet port. The efficiency, η, of the system can be calculated as

$$\eta = \frac{E_o}{E_i} \qquad (2)$$

where, E_i is input energy.

$$E_i = G \times Area_{collector} \qquad (3)$$

Where, G is the global radiation. The efficiency of the system will depend on the cloudiness of the sky, and accordingly, on the proportion of DNI. Concentrated solar-based technology makes use of only DNI. We have also computed the SRCC (solar rating and certification corporation) efficiency, which is provided by the following model:

$$\eta = A_0 + B_0 \left(\Delta T / G \right) \qquad (4)$$

Where, A_0 and B_0 are the coefficients of the efficiency model. The solar unit uses different instruments to note weather status during the experiments. A pyranometer is used to measure global radiation and a pyrheliometer is used to measure DNI at any particular time of instant. The radiation is captured every minute and used for further data processing. Typically the output power depends upon a number of factors such as temperature, wind speed, etc. A weather station has been used which measures humidity, temperature and wind speed. The performance of the CPVT unit can be correlated to different environmental factors, which have been measured during the course of experiments.

RESULTS AND DISCUSSION

To smoothen the discrete data set, the signal processing technique of applying a low pass filter was followed. Figure 3 shows a comparison between global radiation and DNI. The plot shows a strong correlation between DNI and global radiation. Typically, experiments were conducted throughout the day. The water flow rate was maintained at 7.1 l/m^3. However, we have experimented with different flow rate. We observed that the efficiency number does not change significantly with flow rate, but responsiveness of the CST to cloud movement is higher for low flow rate. Figure 4 shows significant efficiency fluctuation for inter-day and intra-day measurement. Most of the testing days were partially cloudy and that might have led to intra-day efficiency fluctuation. Typically maximum efficiency is limited to 65% (neglecting few outlier points), which agrees with the entitlement number for solar to thermal efficiency.

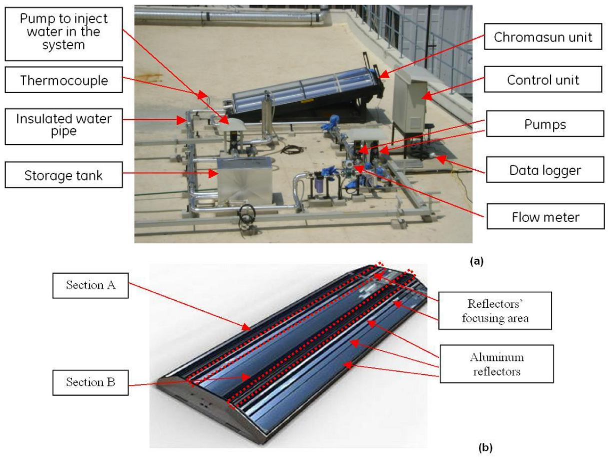

FIGURE 2. (a) Test bench for the system level characterization experiments. (b) Fresnel reflector based CST unit from Chromasun Inc.

An inverse relationship of efficiency Vs. global radiation can be observed in Figure 5. Future work will involve ensuring a consistent inlet temperature and ΔT, while measuring the solar to thermal efficiency.

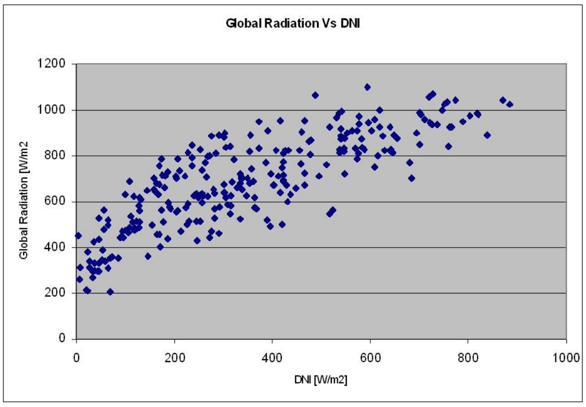

FIGURE 3. We observe a strong correlation between global radiation and DNI

Figure 6 shows a broad scattered distribution of thermal power as a function of DNI. An underlying broad monotonic variation of thermal power with DNI has been captured. The upper limit (UL) and lower limit (LL) (see Figure 6) indicates that most of the data points follow the expected monotonic variation of higher DNI leading to higher thermal power. The outliers or outlying data points leading to scattered data (highlighted by circles in Figure 6) can be explained by presence of a quick cloud movements and inconsistent tracking.

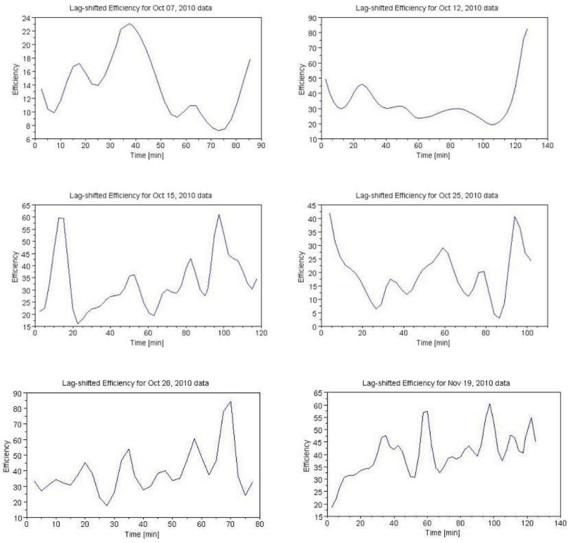

FIGURE 4. We observe significant efficiency fluctuation inter-day and intra-day. Most of the testing days were partially cloudy and that might have led to intra-day efficiency fluctuation.

We also characterized the thermal time constant of the entire flow loop. The theoretical time constant (or thermal time lag) is 245 seconds (or 4 minutes). Experimentally, we do observe variation for different days due to seasonal and environmental factors. However, on an average an experimental time constant of 6 minutes is observed.

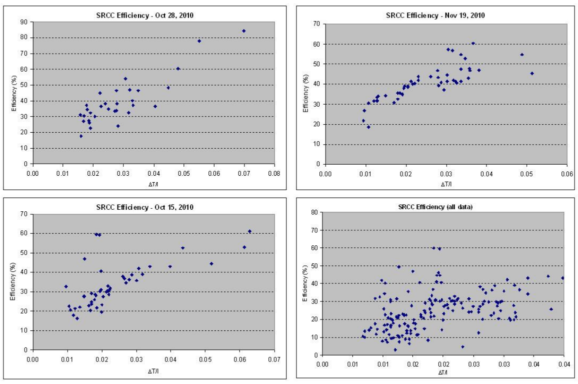

FIGURE 5. Inter-day and intra-day variation of efficiency as a function of ΔT/Insolation. Several days indicate a linear monotonic pattern of efficiency variation. Few days have scattered data.

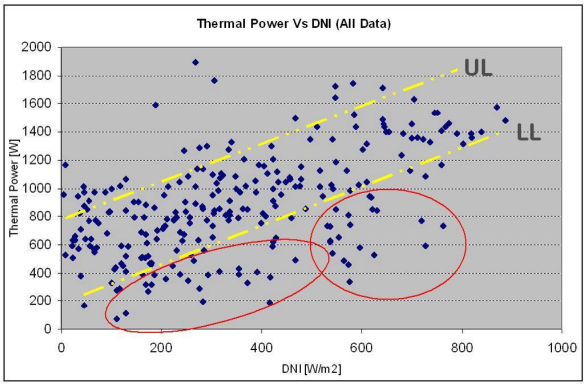

FIGURE 6. Variation of thermal power as a function of DNI.

CONCLUSIONS

We have summarized the experimental setup and methods to characterize a CST unit. This paper highlights the thermal power and system level efficiency of CST. We have established the dependence of thermal power and efficiency on global radiation, DNI, and ΔT/Insolation. We have demonstrated that it is possible to obtain thermal power of greater than 1.6 kW for DNI of 850 W/m^2. We also observe that the efficiency of the system fluctuates significantly and is dependent on global radiation. There is a phase difference (of fall and rise) between thermal power and solar radiation. Tracking is a challenging problem for partially cloudy sky, and fast cloud movements. Optimizing the flow rate can be critical to improve the capacity factor of the CST system. We believe the following topics need to be investigated to improve the CST system level performance:

- Improved tracking
- Improved thermal storage
- Usage of alternate fluid (oil, organic fluid, etc.)

Future work will also involve test-rig upgradation and detailed characterization of a CPVT unit from Chromasun Inc.

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1. www.chromasun.com