A SIDE BY SIDE OUTDOOR PERFORMANCE ANALYSIS OF THREE TYPES OF SOLAR THERMAL COLLECTORS UNDER VARYING RATIOS OF DIRECT AND DIFFUSE RADIATION

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ABSTRACT

Solar thermal collectors of various geometries are available to consumers. While flat plate collector geometry has remained important and unchanged for several decades, non-flat-plate geometry collectors are gaining market share. Studies of non-flat-plate collector performance under high diffuse radiation are limited. This effort investigates the performance of three side by side solar thermal collectors at an outdoor test facility in Western North Carolina. The performance of a flat plate collector, a heat pipe evacuated tube collector, and a compound parabolic concentrating collector is measured. Along with collector thermal performance, detailed irradiance data, including direct normal irradiance, is collected at the site. The primary investigation examines the efficiency slope and Y intercept of the three collector geometries under different ratios of direct and diffuse radiation. Performance results can be used to improve economic models and suggest which solar thermal technologies are best for specific locations.

1. INTRODUCTION

This study will examine how efficiently various solar thermal collectors are able to utilize different ratios of direct and diffuse solar radiation. The study will test three types of solar thermal collectors which will include flat plate collectors, evacuated tube collectors, and compound parabolic collectors in a pressurized glycol solar thermal system at the Appalachian State University Solar Lab. The findings from this study should enable a better estimate of solar thermal collector performance under various real world conditions.

2. REVIEW OF PREVIOUS STUDIES

Worldwide Solar Thermal Utilization

Solar thermal technology allows the capture of solar radiation so that its energy can be transferred to some other material, usually water or another type of heat transfer fluid. On a global scale, solar water and space heating account for 171 GW_T installed capacity as of 2009 (1). The highest installed capacity of solar thermal for domestic hot water production is in China, Australia, Europe, Israel, Turkey and Brazil. In addition many countries in Europe are seeing a growing number of systems used for a combination of domestic hot water (DHW) and space heating applications (1). The United States also has considerable installed capacity of solar thermal however a large percentage of this is in the form of unglazed pool heating applications.

Types of Solar Thermal Collectors

This study focuses on the performance of flat plate collectors (FPC), evacuated tube collectors (ETC) and non-evacuated compound parabolic concentrating collectors (CPC) used in an indirect domestic hot water heating system. Flat plate collectors are the oldest and most established technology, originally developed in the 1950’s by Hottell and Willier (2). Flat plate collector design hasn’t changed much in the last 30 years. Collectors usually come in 4 by 10 feet or 4 by 8 feet sizes. The collectors consist of an insulated box with a glazing material (usually low iron glass) on the side oriented towards the predominant sun direction. Inside the box are a series of copper risers connected to copper fins which are coated with an absorptive material. The higher end flat plate collectors use a selective absorber material which minimizes heat loss and improves overall collector efficiency (3). The heat transfer fluid (HTF) is heated as is circulated through the copper risers inside the collectors.

Evacuated tubes are a newer technology designed to avoid convective and conductive heat loss. The tubes have a number of designs however the most common design uses a double-walled glass construction. The absorber surface is usually coated on the inside layer of glass. Having the double evacuated tube creates a more robust design and minimizes the effect that cold outside air temperatures have on solar heating. The heat pipe design uses the phase change properties of a fluid to transfer heat from inside the evacuated tube to the HTF which flows through the collector manifold. This design is commonly referred to as a heat pipe evacuated tube design. Some have argued that evacuated tubes perform better on less sunny days with high ratios of diffuse radiation relative to flat plate collectors due to their geometry (4).

The third type of solar collector that will be tested in this study is a compound parabolic collector. Originally developed in the early 1970's by Ronald Winston of the University of Chicago (5), the modern CPC looks similar to a flat plate collector from a distance, but it uses different absorber technology. Just as in the FPC, HTF fluid circulates through copper risers inside the collector. Under the risers is a reflective material that has been formed into a compound parabolic shape. As the sun moves through the sky the shape of the highly reflective material concentrates the solar energy onto the copper risers without tracking the sun. This maintains a small incidence angle throughout a longer portion of the day (6). Pramuang and Exell (7) suggest that CPC's are capability of utilizing radiation efficiently for longer periods of the day due to the collectors concentrating properties. They also discuss the collector's ability to concentrate diffuse radiation; however performance relative to other collectors is not clear.

Solar Radiation

About 1.8×10^{14} kW of solar radiation is intercepted by the Earth. About 60% of this reaches the Earth's surface (8). As solar radiation travels from the sun, through the Earth's atmosphere and ultimately to the surface of the Earth, it is affected by scattering, absorption and reflection due to the effects of the atmosphere and the ground (9). The optically active surface of a solar collector is often referred to as the aperture plane in solar radiation discussions. The radiation that reaches this aperture plane of the collector can be divided into three different components. Beam radiation is unaffected in its direction by atmospheric or ground effects (9). It passes unscattered through the Earth's atmosphere and the light rays are said to be parallel. It is often referred to as direct radiation (3). Diffuse Radiation is effected by the scattering effects of various atmospheric conditions (9). Diffuse radiation reaches the Earth's surface from the entire dome of the sky (4), and can be further divided into three parts: uniformly distributed radiation, circumsolar radiation, and Horizon brightening (4). Reflected radiation is reflected off the ground before it reaches the aperture plane of the collector. The amount of reflected radiation depends on the amount of radiation reaching the reflective surface (ground) as well as the albedo of the surface. (9).

Together, beam, diffuse and reflected radiation combine to make up global irradiance. As Anderson and Furbo point out circumsolar radiation is technically diffuse, but is usually accounted for as beam radiation. It is almost impossible to measure the true diffuse radiation, but a pyrheliometer measures beam radiation and a fairly accurate diffuse measurement can be calculated (4). This study is primarily concerned with the measurements of direct and diffuse radiation. The direct beam measurement is subtracted from the global irradiance measurement at the plane of aperture of the collectors to get the measure of the diffuse radiation. The ground reflected radiation component will be incorporated into the diffuse measurement.

Solar Thermal Collector Performance

Collector performance is affected by many conditions present in the outdoor environment however energy production is largely a factor of the relationship between the temperature of the heat transfer fluid, the ambient temperature, and the solar energy incident on the collector (4). Collectors are most efficient when the heat transfer fluid and ambient temperatures are close to each other.

Collector Testing

Collector testing is carried out by a number of organizations worldwide including the Solar Rating and Certification Corporation (SRCC) in the United States, the Research and Testing Centre for Solar Thermal Systems in Germany, and the Institute for Solar Technology in Switzerland (10). These organizations use several standards to test collectors with the ultimate goal of classifying collector performance so that collectors can be compared with one another. Collector testing standards include EN12975, ANSI/ AHSREA 93-2010 and ISO 9806 with the EN12975 standard being the most common. All of these standards parameterize collector efficiency with an optical efficiency (efficiency with no conductive heat loss) and a heat loss term that is slope of collector efficiency versus Ti-Ta/Irr where Ti is inlet collector temperature, Ta is ambient temp, and Irr is irradiance. There are generally two types of solar thermal collector testing methods; steady state and quasi dynamic.

Steady State

The steady state solar thermal testing is undertaken using a highly controlled set of testing conditions. Steady-state testing typically requires strict control of total irradiance, diffuse fraction, incidence angle, ambient temperature, and inlet temperature during testing (11). Due to the tightly regulated testing conditions, outdoor steady state solar thermal testing can be difficult and time consuming to conduct in many regions (12). Shortcomings of the steady state test method include its inability to account for the optical and geometric characteristics of non-flat plate collectors and their ability to transform incident solar radiation into heat (9).

Quasi dynamic

The quasi-dynamic testing standards were developed due to perceived shortcoming of the steady state testing method. It was designed to better represent real world irradiance situations and facilitate outdoor testing in areas of variable weather and irradiance levels (12). Rojas et al. (11) note that the major difference in the quasi-dynamic test method is that the energy gain is measured over short intervals while solar irradiance and ambient temperature are allowed to vary. Steady-state testing requires that testing be conducted around solar noon when the IAM is near 1 and the irradiance is high, but quasi-dynamic testing can be performed for a much larger part of the day. Horta et al. explains that long term modeling using quasi-dynamic results is still new, and more analysis is needed in relating the results of quasi-dynamic tests to long term performance (9). In subsequent studies, Zambolin and Del Col (13) conclude, "The curves obtained with steady state and quasi-dynamic test methods are in agreement within their uncertainty ranges." They also conclude that coefficients obtained using quasi-dynamic test methods can be used for simulation and annual energy production modeling in conjunction with TMY data (13). They also note that limited results are available regarding quasi-dynamic testing of ETC's and CPC's. Side by side testing of representative examples of the three types of commercially available solar thermal collectors under real world operating conditions is needed to determine the ability of the three collector designs to utilize direct and diffuse solar radiation under actual working conditions (10).

3. RESEARCH METHODOLOGY

General Overview of the Research Design

The three collectors used in this study are installed side by side on a south facing roof with a 40º tilt angle at the Appalachian State University solar lab. Heat transfer fluid is fed to each collector through a pressurized glycol loop. Each collector has a thermistor on the inlet and outlet of the collector. This allows the collection of temperature data which is used to calculate the change in temperature of the HTF as it travels through the collector. In addition there is a flow meter that measures the flow of HTF through each collector. Using the change in temperature and the flow, energy produced by the solar collectors can be calculated. This energy data will be compared to the ratios of direct and diffuse radiation during specific time periods in order to calculate each collector's performance.

Instrumentation

One FPC, one ETC and one CPC are installed at 40˚ tilt angle facing 180˚ south azimuth. The flat plate collector is an Alternate Energy Technologies Morningstar MSC-32 4' × 8' unit. The evacuated tube collector is a Solar Collectors SCM-15 15 tube heat pipe unit. The compound parabolic collector is a Solargenix Winston Series 4' × 6' unit. The collector flows are controlled individually of one another. The HTF flows are measured with a Seametrics SB-050 paddle type flow meter. The heat transfer fluid used by each collector is a 50/50 Downfrost and water thermal fluid mixture which runs through an internal heat exchanger on an Alternate Energy Technologies 80 gallon solar thermal hot water tank which is connected to a cooling loop to simulate a domestic hot water draw. This design should ensure that all the collectors are delivered nearly the same temperature HTF through the collector inlets.

The temperatures at the inlet and outlet are measured with Omega 40k thermistor 1/8" immersion probes . Data is logged every 15 seconds and averaged into one minute, five minute, 15 minute and 60 minute data sets with a Cambell Scientific CR1000data logger.

Direct normal irradiance (DNI) is measured with a Hukseflux DR-1 Pyrheliometer (first class). A Minitrak II Solar Tracker is used to track the sun. Global diffuse radiation (GDIFF) is measured with a Hukseflux SR-11 Pyranometer (first class). Total radiation in the plane of the fixed-mounted collectors is measured by a Hukseflux LP02 Pyranometer (second class).

Climate data is measured at a weather station on site. Wind velocity data is measured with a Met-1 034-b wind set. Humidity and temperature are measured with a Campbell Scientific HMP 50 sensor. Precipitation is measured with a Texas Electronics 525 tipping rain bucket. Similar to the data logging on the solar collectors, radiation and weather data is logged at 15 second intervals and averaged into one, five, 15, and 60 minute data sets with a Campbell Scientific CR1000 data logger in order to enable comparisons with the solar thermal collector performance (10).

Data Collection Procedures

Data was collected between September 8, 2012 and January 26, 2013. Five minute data points were selected for analysis.

Data Analysis Procedures

The collector efficiencies were binned with similar Ti-Ta/irr measurements. The efficiency calculations for the data in these bins was averaged and graphed to form efficiency curves. The next step involved the grouping of these calculations based on the ratios of direct and diffuse radiation so that data sets corresponding to similar ratios were grouped together. Because the collectors are side by side during the data collection period each collector is exposed to the same ambient conditions during a specific time period.

In addition to the efficiency curve method described above, a different method of collector comparison was used to account for the variable nature for outdoor testing. The same five minute data that was used to calculate efficiency curves was used for further analysis of collector energy production. The same data cleaning procedures were used (>300 POA irradiance, <10% variation over 10 minutes etc.). The data was organized by time step so that collector energy production could be compared to one another during the same environmental conditions. The time steps were grouped by direct beam fractions. For each time step, the collector that had the highest energy production, based on watt hours/ meters^2, was selected.

Data validation procedures

Data collection took place from September 8, 2012 until January 26, 2013. At the end of the collection period 40,210 lines of five minute data had been collected. A series of data filtering steps were undertaken. Due to shading issues at the study site, data outside of 9AM and 4PM were eliminated. Only data where the flow was less than 1 gpm and greater than 0.3 gpm for all collectors was kept. Negative temperature differences between the intake and outlet of the collectors would result in negative energy values for the collectors and were sorted out. Finally, to reduce sensitivity to collector thermal capacitance and better correlate time, irradiance, and efficiency measurements data that was associated with POA variability greater than 10% in the previous five minutes was filtered out and only data associated with POA irradiance of 300 W/m^2 was used.

Collector Performance Calculations

After the data was cleaned, the x axis variable (Ti-Ta)/Irr was calculated using measured temperatures and measured POA irradiance. The efficiency was calculated and graphed as a function of (Ti-Ta/Irr). Instantaneous efficiency of the collector was calculated using the equation:

$$\varepsilon = (\dot{Q}/A)/I = (\dot{m}c\Delta T/A)/POA$$

where the total power incident on the collector is taken to be the irradiance measured in the plane of aperture (POA) (11).

The x axis values were rounded to the nearest .005 and divided into bins after which the average efficiency value in each bin was calculated.

To investigate collector performance as a function of radiative *quality*, the direct beam fraction was calculated by dividing the component of DNI striking the POA by the measured POA:

$$DBF = DNI_{\perp}/POA$$

4. RESULTS

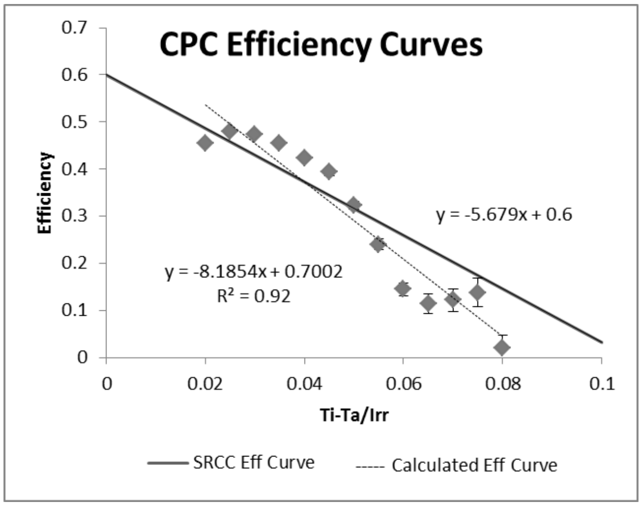

Fig. 1: The data and calculated efficiency curve of the CPC for this study is shown with the SRCC efficiency curve.

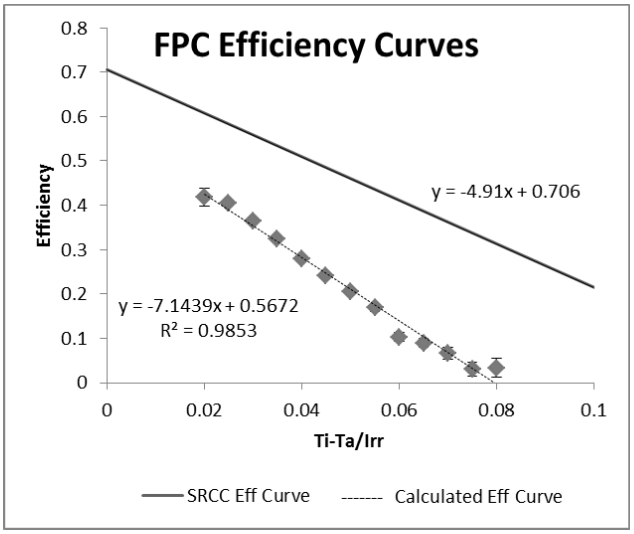

Fig. 2: The data and calculated efficiency curve of the FPC is shown with the SRCC efficiency curve.

The graphs in Figures 1 and 2 represent 3,827 five minute data points.

Ti-Ta/Irr bins with fewer than 20 data points were not used for the calculation of the efficiency curves. These excluded bins were grouped towards the minimum and maximum ends of the x axis (<.02 and >.08).

Due to the variable nature of outdoor testing conditions, a different methodology was used to compare collector performance during different DBF conditions.

The percentage of time steps that each collector performed best was calculated and displayed in table 1 below.

TABLE 1: COLLECTOR PERFORMANCE COMPARISONS

	FPC	ETC	CPC
All DBF	2%	11%	87%
>90% DBF	0%	25%	75%
80-90% DBF	2%	1%	97%
70-80% DBF	4%	1%	95%
60-70% DBF	3%	1%	96%
50-60% DBF	8%	3%	90%
40-50 % DBF	0%	0%	100%
30-40% DBF	0%	9%	91%
<30 % DBF	0%	32%	68%

Unfortunately, the method of comparison shown in Table 1 does not lend itself well to the creation of a model; however it does show which collector performed best at the study site given a specific set of atmospheric conditions. One can see that the CPC collector produced more energy than the other collectors on most occasions. This follows the general trends observed from the efficiency curves that the CPC generally outperformed the FPC. Some trends are observed which deserve further investigation. As the direct beam fraction gets below 40%, the performance of the ETC appears to improve in relation to the other collectors. This improvement gets more dramatic as the direct beam fraction drops below 30%. While the CPC still outperformed the ETC at low DBF's in this experiment, further experimentation should help to clarify the results.

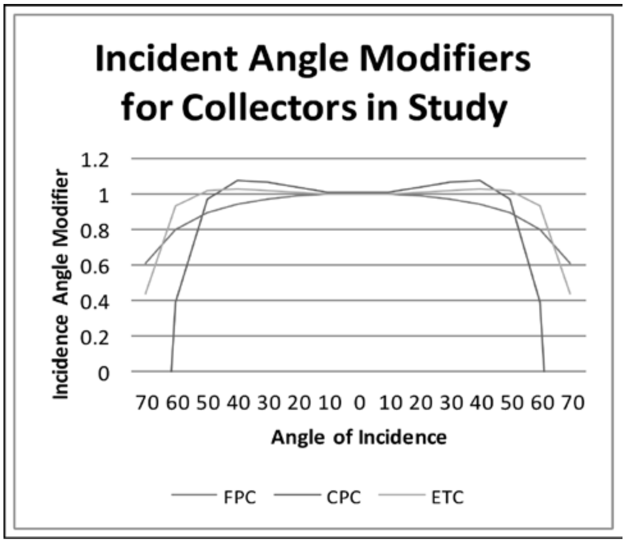

Fig. 3: The incident angle modifiers for the collectors included in this study are shown in the chart above.

It should also be noted that the FPC underperformed in this study compared to its predicted performance according to the efficiency curve calculated by the SRCC. The CPC performed slightly better than the performance predicted by the SRCC efficiency curve; however the slope was steeper than the SRCC curve indicating increased heat loss.

The collector ability to intercept non-normal rays is characterized by the incident angle modifier chart seen in figure 3. It should be noted that this chart shows that both the CPC and ETC have incident angle modifiers greater than one during times of the day of non-normal incidence. Both of these collectors outperformed the FPC in this study, possibly due better utilization of solar radiation in the morning and afternoon.

5. SUMMARY AND CONCLUSIONS

This study began by using a similar methodology as the SRCC for collector testing. Collector efficiency was calculated in relation to inlet temperature, ambient temperature and irradiance for the flat plate collector and compound parabolic collector. As an alternative, a different method of performance analysis was used to compare collector performance to one another. In each methodology, the CPC outperformed the other collectors.

This study was not meant to suggest that the testing conducted by the SRCC is without merit. Indeed, the SRCC has set up a very useful methodology to compare collector performances to one another. The performance characteristics calculated by the SRCC can be used for future modeling of the collectors.

In this specific study, using a specific set of instrumentation and testing procedures, the CPC outperformed the FPC and ETC in most cases. Further study is needed to confirm these findings. In addition, further study is warranted under low direct beam fractions to investigate collector performance.

Solar thermal is not a new technology, but technological advances are showing promise for improved performance. A better understanding of collector performance in specific meteorological conditions can lead to improved modeling capabilities and better recommendations for which collectors will perform best in specific regions given the atmospheric conditions.

For Future Studies

The data analysis process was begun by screening out all data with POA irradiance values below 300 w/m2. Data associates with irradiance values below this level were determined to be too scattered to be used with any level of certainty for the calculation of efficiency curves. Irradiance levels below the 300 W/m^2 benchmark certainly have an effect on efficiency curves and as more data is accumulated, it would be useful to try and calculate efficiency curves for these lower levels of irradiance, especially because these low irradiance levels would often correspond to times of highly diffuse irradiance. For future studies it would be useful to determine how successfully collectors are able to extract solar energy from these low irradiance levels.

6. ACKNOWLEDGEMENT

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7. REFERENCES

(1) International Energy Association. (2009). Renewable Energy Essentials: Solar Heating and Cooling. from http://www.iea.org/papers/2009/Solar_heating_cooling.pdf

(2) SOLCO. (2007). Solar Collectors. Retrieved April 21, 2012, from http://www.solcoproject.net/docs/DELVRBLENGLISH/Solar_Collectors_English.pdf

(3) Duffie, J. A., & Beckman, W. A. (1974). Solar energy thermal processes: Wiley

(4) Andersen, E., & Furbo, S. (2009). Theoretical variations of the thermal performance of different solar collectors and solar combi systems as function of the varying yearly weather conditions in Denmark. Solar Energy, 83(4), 552-565. doi: 10.1016/j.solener.2008.10.009

(5) Winston, R. (1974). Principles of Solar Concentrators of a Novel Design. Solar Energy, 16, 6

(6) Solarbook. (2009). Solar Book: Online solar reference guide. Retrieved April 20, 2012, from http://www.solarbook.ie/solar-incident-angle-modifier.html

(7) Pramuang, S., & Exell, R. (2005). Transient test of a solar air heater with a compound parabolic concentrator. Renewable Energy, 30(5), 715-728.doi:10.1016/j.renene.2004.01.013

(8) Thirugnanasambandam, M., Iniyan, S., & Goic, R. (2010). A review of solar thermal technologies. Renewable & Sustainable Energy Reviews, 14(1), 312-322. doi: 10.1016/j.rser.2009.07.014

(9) Horta, P., Carvalho, M. J., Pereira, M. C., & Carbajal, W. (2008). Long-term performance calculations based on steady-state efficiency test results: Analysis of optical effects affecting beam, diffuse and reflected radiation. Solar Energy, 82(11), 1076-1082. doi: 10.1016/j.solener.2008.01.004

(10) Abernethy, L. (2011). An Empirically Derived Model Regarding the Regional Performance of Flat Plate, Evacuated Tube and Compound Parabolic Concentrating Solar Thermal Collectors Based on Varying Ratios of Direct and Diffuse Solar Radiation. (Masters Research Paper)

(11) Rojas, D., Beermann, J., Klein, S. A., & Reindl, D. T. (2008). Thermal performance testing of flat-plate collectors. Solar Energy, 82(8), 746-757. doi: 10.1016/j.solener.2008.02.001

(12) Fischer, S., Heidemann, W., Muller-Steinhagen, H., Perers, B., Bergquist, P., & Hellstrom, B. (2004). Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2. Solar Energy, 76(1-3), 117-123. doi: 10.1016/j.solener.2003.07.021

(13) Zambolin, E., & Del Col, D. (2010). Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions. Solar Energy, 84(8), 1382-1396. doi: 10.1016/j.solener.2010.04.020