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A Paper on the Testing Procedures and Protocols for Concentrated Solar Thermal Technologies

Tatenda Kanyowa[1], Emmanuel Ndala[2], Garikayi Victor Nyakujara[3], Dr. U Sahoo[4], Dr. Subhra Das[5]
PG Scholar[1, 2, 3], Professor& HOD[5]
Department of Renewable Energy
Amity School of Applied Sciences (ASAS), Amity University Haryana (AUH), Panchgaon, Haryana, India

Abstract:
Interest in solar thermal technologies have grown over the past two decades due to the increasing energy deficit around the globe as well as increasing carbon levels in the atmosphere. Unlike solar photovoltaics, solar thermal technology has the potential to provide both high and low-grade energy which can be used for several applications from household, industrial to electricity generation. This document will focus more on concentrated solar technology (CST) which are essential for the future because they can offer flexibility and potential high dispatch ability in power plant applications. In order to fully utilize CSTs, performance standards of these systems are being setup. These can help to ensure that for a certain CST device, it must meet certain performance criteria in order for it to produce favourable results. Performance standards for these systems also help in allowing interchangeability of certain components. Testing of a CST system is done in several steps depending on the type of system. Usually the most ideal conditions are required to test the performance of a CST system. Clear skies with radiation of 450W/m or above are usually ideal to execute this process. The testing equipment is adjusted so that near steady state conditions are established. CST systems must have high optical efficiency for good performance since they rely on reflection of the direct radiation onto a receiver. Good reflecting materials must be used to guarantee better performance of the system since the system will always have losses which will reduce the expected thermal efficiency of the system. These are some of the parameters and conditions which will be discussed in this paper.

1.INTRODUCTION

Performance of concentrating solar thermal technologies is quite sensitive to design parameters and operational conditions and therefore the task of evolving and implementing a test procedure for the purpose of standardization and certification is quite involving and challenging. Currently a plethora of test standards are being developed for performance evaluation of concentrated solar thermal technologies. With concentrated solar thermal technologies (CST) gaining more prominence, a wide range are available in the market. CST technologies are used for different applications from water heating, cooking, industrial heating and electrical power generation. CST provide a good efficiency range provided there is enough solar radiation which is intermittent in nature. The four main commercial CST technologies are distinguished by the way they focus the sun's rays and technology used to receive the solar energy. These CST technologies are parabolic trough collector, solar tower, linear Fresnel collector and parabolic dish collector. They can be classified according to the focus type i.e. line focus or point focus, depending on the receiver type (fixed or mobile) or considering the concentration level (medium or high).

1.2 Objective

The work contained in this paper was focused on highlighting the performance measuring standards, test procedures and protocols for concentrated solar technologies for the purpose of ascertaining their performance and durability during installation and subsequent use.

1.3 Scope of the work

The scope of the work encompasses the following:

- To discuss test procedures and protocols for measuring performance of concentrated solar technologies
- To discuss equipment and measuring instruments for test set up for CSTs
- To discuss ways and procedures for testing the performance of CST based systems at site and instruments required for that purpose

2. LITERATURE REVIEW

2.1 Opportunity and Challenges for Concentrated Solar Technology:

Over the years, CSTs have failed to make its stamp in the market for several reasons with the major one being competition from fossil fuels and other renewables such as PV and wind. However it should be noted that CSTs offer greater flexibility than renewable energy sources in particular PV technology. The potential benefits offered are not limited to dispatchable high energy value, operating reserves and reliable system capacity. J.Tomaschek et al highlights the flexibility and dispatchability of concentrated solar power (CSP) which results in energy production during periods of peak demand, which can be a sustainable future solution to addressing power problems and to replace non-renewable power plants. [1]. Another benefit of CSP technologies when compared to other renewable energy sources is that they can overcome the intermittent nature of solar or wind energy by using thermal storage. Thermal storage gives CSP systems the ability to generate power during low radiation hours as well as during the night depending on the storage capacity. A huge amount of oil and electricity per year is used in industries for steam generation below 250^{o}C and for water and air heating alone. Use of high grade heat from fossil fuels needs to be minimized especially considering the availability of clean cheaper options. CSTs are now becoming an economically viable option especially considering most countries are reliant on fuel importation and a majority of people in the rural areas have little or no access to electricity. This adoption could potentially save billions of dollars, improve our climate situation, create more job opportunities and meet the energy demand by of the ever-growing population. [2]. To fully adopt the idea of the CSTs, focus should not only be emphasized on the capital investment involved but the potential grid benefits that it brings. However, cost investment should drastically go down so as to compete with other energy sources. There are also certain challenges associated with CSTs which include, technological uncertainty, space rooftop application, quality and durability of mirrors of the system is uncertain, intermittency and unpredictability of the weather and demand and supply deficit of good quality mirrors.

2.2Types of tests for concentrated solar thermal technologies

Different tests have been implemented to measure the performance of CSTs by several institutions such as the American society of mechanical engineers (ASME), National Renewable Energy Laboratory (NREL) etc are coming up with performance standards for different type of collectors. An example is ASME's performance test code (PTC). ASME has a specific test code for concentrating solar systems called PTC-52. [3]. Although these standards differ in their own respects, they mostly focus their results based on system and durability of their components. Basically, the testing process includes:

i. Testing of performance at site and instruments required for the same or mobile test system

ii. Performance measurement tests using thermic fluid, high pressure hot water and steam system at test centres-immobile test setup

Three basic tests have been proposed for measuring performance of the systems and these are based on, thermic fluid, pressurized hot water and steam generation. The most common of the tests being based on thermic fluid for the analysis of the system. [4]. Thermal tests on CST based solar collector are conducted to evaluate the extent of their capability to provide useful thermal output under given climatic conditions. The methods stated are entirely based on quasi steady conditions of operation. [3]. The data generated from these tests allow us to obtain values of efficiency as a function of solar irradiance, ambient air temperature and inlet fluid temperature to determine the time response characteristics of collector and to find out dependence of efficiency on the incident angle at various sun and collector positions.

2.3Testing Equipment and Conditions

Measurements of solar radiation

Class I or better, pyranometers shall be used to measure the solar radiation. Before each test the pyranometer should be checked for dust, soiling etc. on the outer dome and it should be cleaned if necessary. Class I or better pyranometers equipped with a shading ring or alternatively a pyrheliometer together with a pyranometer shall be used to measure the diffuse short-wave radiation.

Temperature measurements

Three temperature measurements are required for solar collector testing. These are the fluid temperature at the collector inlet, the fluid temperature at the collector outlet, and the ambient air temperature. The temperature of the heat transfer fluid at the collector inlet and outlet shall be measured to a standard uncertainty of 0.1 K.

Flow rate measurement

Mass flow rates may be measured directly or, alternatively, if the density is known, they may be determined from measurements of volumetric flow rate and temperature. The standard uncertainty of the liquid flow rate measurement shall be within ± 1 % of the measured value, in mass per unit time. The flow meter shall be calibrated over the range of fluid f low rates and temperatures to be used during collector testing.

Preparation of Apparatus

- The collector shall be installed and aligned properly according to a test method approved by the manufacturer.
- Collector surfaces exposed to the environment shall be cleaned at the beginning of each test day according to the manufacturer's recommended procedures.
- The geographical location (latitude and longitude) of the collector shall be determined and reported to an accuracy of ±0.1°. Where applicable, the orientation of any fixed collector axis shall be measured to an accuracy of ±0.1 % and reported.
- The pyrheliometer and pyranometer shall be inspected at the beginning of each day at which time the outer glass surface shall be cleaned and dried if dirt or moisture is present.
- Any evidence of moisture or debris in the interior of the instrument shall be cause to remove it from service.
- Calibration of instruments shall be checked before starting the tests.

Ambient Conditions

- The direct normal solar irradiance shall not be less than 450W/m
- The average value of the surrounding air speed shall be below 5m/s
- The ambient temperature will vary place to place, however should be taken so that the fluid in the piping and receiver does not get condensed/ frozen

N.B The system shall be tested over its operating temperature range under clear sky condition for determining its efficiency. The measurements are carried out under quasi steady state conditions as shown in the table below.

Table .1. Parameters for testing CST

Sr. No	Parameter		Deviation from the mean value over the test period
1	The normal beam radiation		+/- 4% during the interval of measurement
2	Surrounding air temperature		+/- 1°C
3	Fluid mass flow rate		The flow rate shall be held stable to within 1% of the set value during each test period and shall not vary by more than +/- 10% of the set value from one test period to another
4	Receiver fluid inlet temperature		+/- 0.2°C or 1% of change in temperature

Quasi-steady state conditions

A collector may be considered to have been operating in quasi-steady state conditions over a given test period if none of the experimental parameters deviate from the mean values over the test period by more than the limits given below. For the purpose of establishing that a quasi-steady state exists, average values of each parameter taken over successive periods of 60 s shall be compared with the mean value over the test period.

Table .2. Quasi-steady state conditions

Sr. No (1)	Parameter (2)	Deviation from the mean value over the test period (3)
i.	The normal beam radiation	+/- 4% during the interval of measurement
ii.	Surrounding air temperature	+/- 1°C
iii.	Fluid mass flow rate	+/- 1% of rated flow rate of system
iv.	Receiver fluid temperature	+/- 0.2°C or 1% of change in temperature

Test procedure

Start operation of the collector as per the procedure given by manufacturer and record data. Data points which satisfy the conditions given under Quasi-steady state conditions shall be obtained for at least four inlet temperatures spaced evenly over the operating range of receiver. One inlet temperature shall be selected such that the mean fluid temperature in the receiver lies within ± 3 ˚C of the ambient temperature in order to obtain an accurate determination of optical efficiency. At least four independent data points shall be obtained for each fluid inlet temperature to collect a total of 16 data points.

Measurements

a) Collector aperture area
b) Global solar irradiance
c) Diffused solar irradiance at the collector aperture
d) Direct Normal Irradiance (DNI)
e) Surrounding wind speed
f) Surrounding air temperature
g) Temperature of heat transfer fluid at the receiver inlet
h) Temperature of heat transfer fluid at the receiver outlet
i) Mass flow rate of the heat transfer fluid

3. DATA CAPTURING

The data capturing process begins after the system acquires the quasi-steady state condition. It should be noted that regardless of the ways of capturing data for the determination of thermal performance irradiance and fluid temperature shall be monitored at not greater than 10 seconds intervals such that variations in irradiance and fluid temperature stability can be assessed during all periods of quasi-steady state, before and during testing. [5].
A data point for any variable shall be the average of at least 10 observations taken at intervals of no greater than 30 seconds. Each data point must meet all the requirements for quasi-steady state conditions as depicted in table 2.

3.1 Performance Equations of CSTs

The performance of CST based solar collector operating under steady state conditions can be described by the following equation;

$$\frac{Q}{A} = \eta_0 \times GTI \times Cos\theta \times K_{\theta t} \times K_{\theta l} - a_1(T_m - T_a) - a_2(T_m - T_a)^2 \quad (1)$$

Where $K_{\theta l}$ is the longitudinal incidence angle modifier and $K_{\theta t}$ is transversal incidence angle modifier and Cosθ is the angle of incidence of the sun's rays. The intent of following procedure is to generate sufficient incident angle modifier data K_θ to characterize the collector thermal performance over the full range of operating angles that will be encountered. Longitudinal incidence angle modifier $K\theta_L$ can be calculated with the angle of incidence caused by declination of the sun. Transversal incidence angle modifier $K\theta_T$ can be calculated with the angle of incidence due of sun movement from morning to evening.

Useful heat gain

The useful energy extracted by the receiver for hot water or thermic fluid based system is expressed as follows;

$$Q = mc_f(T_0 - T_i) \quad (2)$$

Where m is the mass flow rate of heat transfer fluid in Kg/s, C_f is the specific heat of the transfer fluid in J/(Kg°C) and T_o and T_i are the temperature of heat transfer fluid leaving and entering the collector respectively in °C.

Efficiency Equation: The thermal efficiency solar collector system is defined as a ratio of the actual useful energy collected to that of the solar energy intercepted by the solar collector, which can be expressed by the following;

$$\eta = \eta_0 - a_1\left(\frac{Tm-Ta}{Ibn}\right) - a_2\left(\frac{Tm-Ta}{Ibn}\right)^2 \quad (3)$$

OR

$$\eta = \eta_0 - a_1\left(\frac{Tm-Ta}{Ibn}\right) - a_2\left(\frac{Tm-Ta}{Ibn}\right)^4 \quad (4)$$

The later equation is used for temperatures more than 200^{o}C.

Computation of thermal efficiency

The instantaneous efficiency η shall be computed form the following expression;

$$\eta = \frac{m*Cp\ (To-Ti)}{Ibn*Ap} \quad (5)$$

An appropriate value of C_p at mean fluid temperature shall be used for equation (5). If m is obtained from volumetric flow rate measurement, then the density shall be determined for the temperature of the fluid in the flow meter. The instantaneous efficiency shall be represented graphically as a function of (T_m – T_a/ I_{bn}). All data points shall be plotted along with a statistical curve fitting using least square.

Computation of optical efficiency

The optical efficiency is calculated from equation (1). A graph is plotted between instantaneous efficiency against (T_m – T_a/ I_{bn}). The intercept of curve on y-axis is the optical efficiency. Alternatively data is collected by maintaining near zero heat loss conditions by selecting inlet temperature such that mean fluid temperature in the receiver lies within +/- 3^{o}C of the ambient temperature (T_m = T_a).

Computation of heat loss coefficients (a_1, a_2)

The test shall be conducted at least four inlet temperatures spaced evenly over the operating temperature range of solar collector to determine the values of a_1 anda$_2$. Multiple Linear Regression (MLR) shall be used to determine a_1 anda$_2$ using the data collected.

Determination of Incident Angle Modifier

Determination of incident angle modifier shall be done by collecting data on heat gain by the mass flow rate specific heat product (m*C_p) and temperature difference between inlet and outlet of the collector. While maintaining the collector within +/- 2.5^{o}C all the angle of incidence specified below the inlet temperature of heat transfer fluid shall be maintained within 1^{o}C. The incident angle modifiers can be determined from the following equation;

$$K(\theta) = \frac{\eta_0(\theta)}{\eta_0\ (\theta = 0)} \quad (6)$$

The efficiency values are determined in pairs, where each pair includes a value of efficiency before solar noon and second value after solar noon. The average incident angle between the collector and solar beam for both data points is the same. The efficiency collector for the specific incident angles should be considered equal to average of two values. Data shall be collected for incident angles of about 0, 30, 45 and 60^o. It should be noted that each CST has its own modified equation for performance depending on the tracking mechanism and the type of point focus.

4. TEST REPORT

A report of this nature should be generated after conducting the test for the CSTs

Collector Information	Test Data and Results
1.Technology type	Location-Latitude, Longitude
2.Manufacturer	Date
3.Dimension and Area	Collector orientation, mounting
eceiver data- storage, dimensions, material, coatings	Operating conditions- operating temperature, pressure
5.Glazing- shape, dimensions, materials	Calculated optical efficiency
racking and drive mechanism description as applicable	Ambient conditions- solar radiations, ambient temperature, operating temperature
	Calculated first order and second order heat loss coefficients
	Calculated incidence angle modifier at different angles

Approach for selection of CSTs

Selection criteria for CSTs should be based on the cost efficiency of the technology for process heat and the optimal/ efficient use of solar thermal technology. Below is a typical graph showing the performance of various CSTs. The CSTs perform differently due to the incident angle modifier and first and second order heat loss coefficients. Hence focus should not be only on the cost but the intended use of the particular technology.

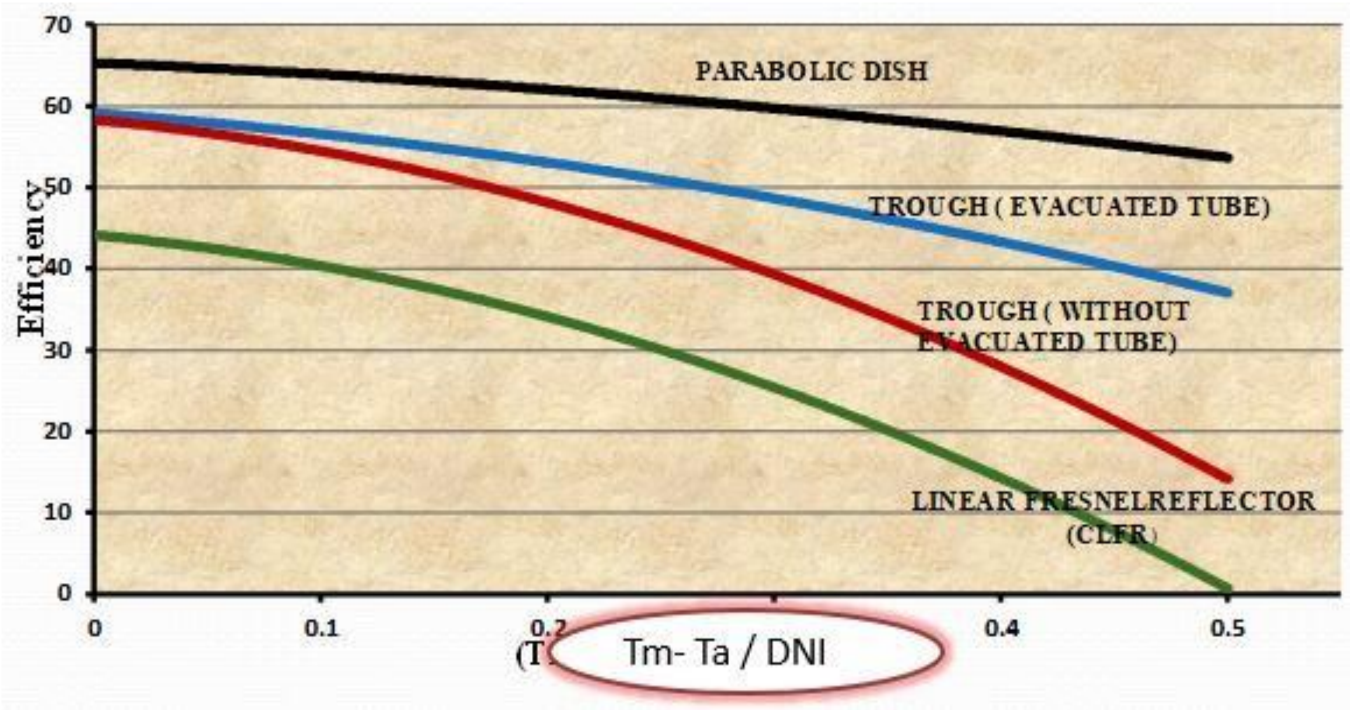

Figure.1. Performance of different CSTS and related efficiencies

Table.3. Operating parameters associated with CSTs

Technology	Cosθ	$K\theta_T$	KθL
Parabolic Dish	X	X	X
Parabolic Trough Collector	Yes	X	Yes
Schieffer Dish	Yes	X	Yes
Compound Parabolic Collector	Yes	Yes	Yes
Linear Fresnel Lens	Yes	Yes	Yes

5. CONCLUSION

Careful consideration must be made in the choice of technology that is best suited for its application. There is a tendency of paying attention to the cost associated with the technology at the expense of its efficiency associated with that particular function. Therefore it should be noted that the user should have a vast amount of knowledge when choosing a particular technology suited for a particular application. Otherwise solar thermal technology will not be utilized to its full potential. There is need for the user to know the optical and thermal efficiency of the system and how it performs under certain conditions. The amount of losses that can be encountered during certain conditions. Although solar thermal is already cost competitive with conventional technologies, barriers are still present. These hurdles include high upfront investment and lack of trained people which keep people from choosing solar heating and cooling. More research and development could jump start the adoption of solar heating and cooling in emerging areas such as industrial processes and cooling. This development and success depends on funding from private and government institutions.

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