Optimizing Thermal Performance in Parabolic Trough Solar Power Systems: An Experimental Design and Analysis

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Abstract. The efficiency of a Parabolic Trough (PT) Solar Power Plant heavily relies on its thermal performance. Modern technology has allowed for the creation of more efficient methods of producing steam and of collecting solar energy for thermal power generation. Ministry of New & Renewable Energy (MNRE) built and tested an 11.1 m² parabolic trough concentrator (PTC). A system that generates steam indirectly by using concentrating solar power (CSP) is examined. The study examined absorbers' thermal properties, thermal efficiency of combined thermal exchangers, concentration ratio, heat efficiency, and steam generation to determine their influence on energy efficiency. The experimental findings display that 557.85 watts of energy are absorbed by the PTC receiver. The PT solar plant system has a thermal energy efficiency of 25 to 29 % and a concentration factor of about 200 on average. The parabolic trough concentrator generates a maximum of 9.1 kg.h⁻¹ of steam.

Keywords: Heat Transfer, Solar Power, Efficiency, Steam, MNRE, Parabolic Trough.

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1. Introduction

The concentrating solar power (CSP) technology has a wide range of applications including desalination, solar cooling, refrigeration, heating in industries, and electricity generation [1, 2]. The International Energy Agency (IEA) forecasts that the capability of Concentrated Solar Power (CSP) installations will rise to 25 GW and 800 GW by 2020 and 2050, respectively [3]. Several studies have demonstrated that breakthroughs in Concentrated Solar Power (CSP) technologies have led to enhancements in steam production. Researchers [4] proposed a concept for straight steam production in CSP plants. A modelling technique was created to forecast the efficiency of a Concentrated Solar Power (CSP) Plant utilizing straight steam production technology. The output of a 5MW electric direct steam production solar plant, developed as part of the INDITEP project, was predicted using three distinct modelling platforms: Thermoflex, TRNSYS, and Octave [5, 6]. Solar photovoltaic systems offer numerous benefits such as enhanced efficiency, flexibility, power density, operational expertise, and compatibility with both renewable and fossil fuels. Parabolic trough collectors have been shown to be very effective in a number of applications, according to research [7, 8]. These include steam generation and large-scale power generation with excellent dispatch. Researchers developed a method to assess the effectiveness of a PTC-assisted solar absorption heat pump (AHP) system [9]. A solar-assisted AHP system to heat water supplies and buildings during winter. Experiments were conducted to compute the optical and thermal losses of the collectors. Researchers [10, 11] examined the efficiency of a photovoltaic heating system that utilized an oil/water heat exchanger (OWHE) and an AHP. Two methods utilized for room heating were OWHE and AHPs. During brief periods of high Direct Normal Irradiance on overcast days, the AHP system was beaten by the OWHE system. In addition to producing saturated steam for 8 hours at a flow rate of 33 kg/h with a quality above 0.6, the study also demonstrated that the collector's efficiency is suitable for connecting to the steam engine. Researchers [12] compared a parabolic trough solar collector in Iran that generates thermal energy in different climates to conventional nanofluids and performed a thermal and optical analysis of the collector. Solar energy capacity was determined in various towns in various climates using PTC. Researchers [13, 14] developed the technique for testing the optical effectiveness of large PTCs on-site. The approach is predicated on the energy balancing of the following: heat gain, end loss, optical loss, cosine loss, and incoming solar radiation. The 310 kWt PTC experiment rig made use of the technology. In close agreement with the LS-3 collector's efficiency of 77%, the optical efficiency is estimated to be approximately 77%. Researchers [15] looked into the thermal efficiency of the state-of-the-art, large-aperture PTC from Sky Fuel. A sophisticated and cost-effective parabolic trough collector, partially financed by the Department of Energy (DOE) and created by Sky Fuel, Inc, designed for thorough performance and efficiency evaluation. The study examined several aspects of optical efficiency, including solar tracking, optical lasers intercept, heat loss of appropriate receivers in molten salt, and operation in HTF molten salt. Researchers [16, 17] used a PT solar concentrator to create a system that could generate heated water and moderate temperature steam. Using three PTCs, moderate-temperature steam and hot water were generated. The study of the PTC array's performance included the investigation of several criteria. It was demonstrated that PTC is theoretically possible for usage involving thermal energy up to 150°C. In their study on PTC design for solar energy harvesting, Researchers [18] used both experimental and simulation methods. We evaluated and assessed the newly built PT solar collector's performance. Use of the collector as a test bed in a continuing solar thermal investigation makes it possible to analyze novel PTCs, such as...
surface materials and thermal collecting elements. An analytical formula was developed by Researchers [19, 20] to characterize the efficiency of a PT solar collector. The thermal efficiency was calculated using PTC’s heat performance and the five criteria of this model. The efficiency of a PT solar collector was investigated on an annual basis [21]. Three separate solar tracking systems in different climate zones of China were used to build a transient heat transfer model that simulated the dynamic behaviour of a PTC device. In regions with abundant sunlight, the yearly heat accumulation was about four times higher compared to regions with no sunlight using the same sun tracking technique. When sunrays are concentrated, heat flux forms unevenly beyond the absorber tube. Researchers performed a 3-D thermal-structural analysis on a PTC absorber tube to study how tube deflection impacts optical efficiency. Numerical methods were employed to calculate the 3D distribution of temperature and thermal expansional of tube resulting from the unequal sun flux within the tub. An analysis was conducted on the local concentration ratio, distribution of temperatures, and thermal expansions, considering the stipulated parameters. Simulating and improving a PTR with an irregular heat flow distribution was the focus of a study by researchers [22]. Simulated studies of PTRs and the approaches for calculating NUHF were part of the study that introduced a NUHF of PT. By inserting eccentric and concentric pipes into a PT solar collector for molten salt, Researchers [23] showed that heat transmission may be increased. A model for a 3D simulation is made. A parabolic trough receiver (PTR) with a NUHF and a detailed distribution of temperatures was successfully simulated using a combination of FLUENT and an MCRT code.

2. Experimental Device Description

An indirect steam generator using a PTC is described in this section. The collector comprises four components: a receiver, a reflector, a hydraulic circuit and a solar tracking system. The SPT is built from galvanized steel and has 2.5 mm thick aluminum sheets covered with a reflective coating on the inside to optimize the amount of sunlight that reaches the absorber. The Parabolic Trough (SPT) system's reflector can rotate around a horizontal axis aligned with the North-South direction to maximize solar exposure, with one degree of freedom fixed in the East-West direction. The concentrator consists of a parabolic shape with a 2.8 m diameter aperture, a focal length of 0.837 m, an opening angle of 76.3° and an aperture area of 11.1 m². The parabola is covered with a thin, lightweight, and cost-effective aluminized material. The SPT uses a single-axis tracker for its sun tracking technology. Two electric jacks controlled by two electrical circuits allow the east-west-oriented SPT to rotate horizontally along the north-south axis. Two arms hold up the SPT's cylindrical receiver, which is positioned at a linear focus. The two 4-meter-long concentric tubes that make up the SPT receiver are vacuum tubes constructed of glass and steel. A selective coating with a 0.0016 m thickness and an aperture diameter of 0.08 m is present inside the inner tube. A black material coats the object to increase its absorption of sunlight. A 0.14 m inner diameter and 0.004 m thick glass cover is used to encapsulate an inner tube in order to reduce thermal heat losses to a minimum. The glass tube has a transmissivity of 0.95. A vacuum had been created in the space between the inner tube and the windshield. A solar collector works by reflecting and concentrating the sun's rays onto a receiving surface. In hydraulic systems, thermal oil soaks up the solar reflected rays.
The oil tank and pump, receiver, water pump and tank, and mixed heat exchanger are the six constituents of the SPT hydraulic system of the apparatus (Fig. 1). The collector focuses and redirects the solar rays onto the absorber by reflection and concentration. The solar energy is absorbing and collected by a Transfer of Heat Fluid (HTF) through the absorption. Using the thermal energy transmitted between oil and water, a mixed heat exchanger will be employed to generate the high temperatures required for steam production. Pumps for the water and oil systems return the relevant fluids to their corresponding storage tanks. Two expansion tanks are included in the SPT hydraulic circuit for safety reasons.

3. Numerical Model

3.1. Thermal Analysis

An energy analysis of the solar parabola and PTC can be performed using the concepts and equations discussed in this section. The solar concentrator's (SPT) effectiveness is dependent on the thermal oil's absorption of heat while passing through a solar heat exchanger (SHE). The formula for this is the difference between the amount of heat lost to the environment (Qp) and the amount of solar power absorbed by the receiver (Qa) [24].

\[ Q_a = m_{Oil} C_p - \text{oil} (T_{out}^{\text{Oil}} - a_b - T_{in}^{\text{Oil}} - a_b) = Q_a - Q_p \]  

(1)

\[ Q_a = \eta_{op} I A_{ap} \]  

(2)

Cp-oil represents the oil heat capacity, m-oil represents the oil mass flow rate, and \((T_{out}^{\text{Oil}} - a_b - T_{in}^{\text{Oil}} - a_b)\) represents the temperature differential between the oil's outlet and inlet. The optical efficiency, denoted as \(\eta_{op}\), is calculated to be 0.85. The optical characteristics of the material and the collector's form determine the efficiency. The variable i symbolizes the quantity of direct solar energy that hits the collector, whereas \(A_{ap}\) indicates the solar concentrator aperture area.
The thermal efficacy of the collector is calculated by dividing the total solar energy input by the usable energy output [25].

\[ \eta_{en} = \frac{Q_u}{Q_a} \]  

(3)

An average system concentration factor is:

\[ C_R = \frac{A_r}{A_{ap}} \eta_{en} \]  

(4)

Ar is the symbol for the solar concentrator's receiver area.

The thermal efficacy of the absorber is determined by dividing the optical efficiency by the thermal efficacy of the solar concentrated system [26, 27].

\[ \eta_{ab} = \frac{\eta_{en}}{\eta_{op}} = \left( 1 - \frac{Q_p}{Q_a} \right) \]  

(5)

Heat losses to the environment from the parabolic trough receiver are determined by these factors:

\[ Q_p = U_L A_r (T_r - T_a) \]  

(6)

To evaluate the overall heat transfer coefficient (UL), one must combine the convective, conductive, and radiative heat transfer coefficients using the following formula, as shown in reference [28] (Fig. 2).

\[ U_L = \left[ \frac{A_r}{A_{gc}(h_{gc-a}+h_{r,gc-a})} + \frac{1}{h_{r,gc-r}} \right]^{-1} \]  

(7)

\[ h_{c,gc-a} = \frac{Nuk_{air}}{\pi D_{gc0}} \]  

(8)

The Nusselt value for this concept is given by the glass cover's outside diameter, Dgc, 0. The linearized radiation equation is used to find the radiation coefficient for transfer of heat from the glass to the environment [29, 30].

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**Fig. 2. PT Solar Collector with a Cylindrical Absorber**

Agc = Parabolic trough absorber's glass cover area.

The convectional transfer of heat coefficient among the atmosphere and glass cover is represented as c, gc-a.
\[ h_{r,gc-a} = \varepsilon_{ge} \sigma (T_{gc} + T_a)(T_{gc}^2 + T_a^2) \] (9)

\( T_{gc} \) = Temperature of the glass cover
\( \varepsilon_{ge} \) = Emissivity
The symbol \( a, bc-f \) represents the coefficient of radiation heat transfer from the glass cover to the receiver [31-32].

\[ h_{r,gc-r} = \frac{\sigma(T_{gc}+T_r)(T_{gc}^2+T_r^2)}{1 - \varepsilon_r A_r - \frac{1}{A_{gc} \varepsilon_{gc} A_{gc} - 1}} \] (10)

3.2. Quantification of Steam Generation

The equation provided calculates the amount of steam generated during the test duration by expressing the thermal energy of steam.

\[ Q_{st} = m_s H_{sh} \] (11)

\[ m_s = m_2 - m_1 = \rho_w \cdot (V_2 - V_1) \] (12)

Whereas,
\( V_1 \) = the volume of remaining water
\( V_2 \) = the volume that was measured of water in the tank
\( H_{sh} \) = Enthalpy of superheated steam
\( \rho_w \) = Water density
\( m_s \) = Evaporated water mass
\( m_2 \) = Calculated amount of water
\( m_1 \) = Amount of remaining water

4. Experimental Investigations

Parabolic trough solar collectors have been the subject of experimental study. Fig. 3 shows the short changes in relative humidity and ambient temperature that were recorded throughout the experiment. The experiment experienced peak global solar radiation of 910 Wm\(^{-2}\), an average relative humidity of 80%, and the greatest ambient temperature of 34°C at noon.
Fig. 3. Comparison of the Relative Humidity and Ambient Temperature

Fig. 4. The Temporal Variations of the Oil Temperatures in and Outlet the Absorber
Studying absorbed energy and absorber efficiency by the receiver is essential for SPT and SPD devices. Fig. 4 illustrates the variations in the temperatures at the inside and outside of the work fluid (Transcal N) circulating in the receive end of a PTC. A mass flow rate of 0.018 kg s\(^{-1}\) was used to circulate the working fluid. The Fig. 4 clearly indicates that 76°C at noon is the optimal exit temperature for the SPT absorbers. Fig. 4 illustrates that the parabolic trough concentrator's solar heat exchanger has an average temperature differential of 12°C between its oil input and output. The SPT outlet fluid takes longer than one hour to start climbing in temperature and remains elevated until 3:00 PM.

4.1 Concentration Ratio and Thermal Efficiency of SPT and SPD

According to the experimental data in Fig. 5 and Equation (10), the parabolic trough solar receiver absorbs 557.85 watts of energy. Mechanical considerations, hydraulic circuit, solar tracking system, and optical characteristics, all impact the thermal efficiency of a solar concentrator. The last parts analyze different criteria and achieve them through evaluations of the systems' thermal efficacy. The concentration proportion for parabolic trough, experimental thermal energy efficiency, and parabolic dish systems was evaluated using mathematical expressions (3) and (4), in accord with the energy balance. The changes in the concentration proportion and SPT thermal efficacy are displayed in Fig. 6. The thermal efficacy of the PTC ranges from 25% to 29%. Fig. 6 also displays the change in SPT concentration ratio over time. An average concentration factor of about 200 is achieved by the PT solar collector. A rise in the thermal efficiency of the concentrator leads to a higher concentration ratio.

![Graph](image_url)

**Fig. 5.** Evaluation of Global Solar Radiation and Solar Concentrated Energy
4.2 The Production of PT and Dish Collectors using Steam

The heat exchanger turns some of the hot water into steam, which is then released into the air. The remaining water is redirected to the storage tank. We measured the steam output by contrasting the amount of water in the tank at the beginning with the amount of water at the end. The mass of steam and heat energy of steam collected at various pressure levels throughout the test time are shown in Fig. 7. Steam and its heat energy have higher values at low pressure and decrease as pressure rises. The steam created reaches a maximum value of 9.1 kg h⁻¹ as seen in Fig.7.
MNRE researchers conducted a study testing a Solar Parabolic trough, a 2D concentrator device used for indirect steam generation. The SPT system's receiver tube, with its large heat transfer area, generates indirect steam by transferring heat to the mixed heat exchanger. An average concentration factor of approximately 200 is achieved by PTCs, and their thermal energy efficiency ranges from 23% to 33%. According to the research, an efficient PTC receiver may produce steam up to 5.1 kg h⁻¹. The heat exchanger returns part of the heated water to the tank and releases steam into the air; the other part is returned to the water tank. Under low pressure conditions, the system produces more steam, which transports more heat energy. The SPD system can generate steam at a maximum of 9.1 kg h⁻¹ when using the SPT system.

References