

Theoretical Review on Influencing Factors in the Design of Parabolic Trough Collector

S. N. Vijayan, S. Sendhil Kumar

Abstract—Recent years have an upward trend in the research of renewable energy sector, due to the low availability of resources and huge consumption of conventional energies. Considerable renewable energy can be achieved from the available solar power with the utilization of collecting systems. Parabolic trough concentrating collector systems are mostly used to utilize maximum availability of solar power. This paper reviews the contributing factors for the overall performance of parabolic trough collectors. Its performance depends on the operating parameters such as the type of receiver and the collector material, medium of heat transfer, type of application and various climatic conditions.

Keywords—Solar radiation, parabolic trough collector, thermal analysis, efficiency.

I. INTRODUCTION

CONSUMPTION of energy is based on the utilization of conventional energy sources. Requirements of conventional energy resources are getting decreased due to the release of high toxic gases which affects the green house causing climatic changes with natural disaster. To overcome these problems it is necessary to find a renewable energy sources providers. In solar systems, heat is transferred from the sun to water or any other medium which captures the heat as it circulates through the receiver pipe. The hot water thus produced is finally stored in a tank for domestic use [1]. In solar thermal power production, concentrated collectors are used for producing high temperature levels with high thermal efficiency with minimum collecting area [2]. Non concentrating collectors were used for low temperature applications. A concentrator is used instead of a non-concentrating collector at high temperatures [3]. This paper reviews the factors to be considered for the improvement in the design of parabolic trough collector.

II. PARABOLIC TROUGH COLLECTOR

A Parabolic Trough Collector [PTC] consists of a solar collector [reflector] made of reflective material such as glass, aluminium, stainless steel. It is used to receive the intensity rays from the sun and reflect to the receiver mounted centrally on the focal line of the collector. The receiver comprises an absorber tube inside an evacuated glass envelope which is generally a coated stainless steel or copper, with a selective

coating to absorb the solar radiation, but emits low level of infrared radiation. A fluid is circulated through the absorber tubes to collect the solar energy and transfer the heat to the steam generator or the heat storage system [4]. The main components of a solar thermal collector are [i] Collector [ii] Receiver [iii] Fluid or heat transfer medium [iv] Tracking device [v] Storage tank. [5]. Fig. 1 shows the physical model of trough collector with all its accessories. In this collector solid plug is inserted in the absorber tube along the focal line of collector. Evacuated space prevents the heat losses by arresting the reflected radiation from the tube [6]. The stages of energy transfer process are shown in Fig. 2. The diagrammatic representation of the energy transfer process in a parabolic trough is illustrated in Fig. 3 High intensity rays fall on the reflector which reflects the intensity rays to the receiver tube mounted in the focal line. It receives the heat from the rays through a pipe and the emitted rays are arrested by the glass cover. High pressurized steam is generated through the heat exchanger [7].

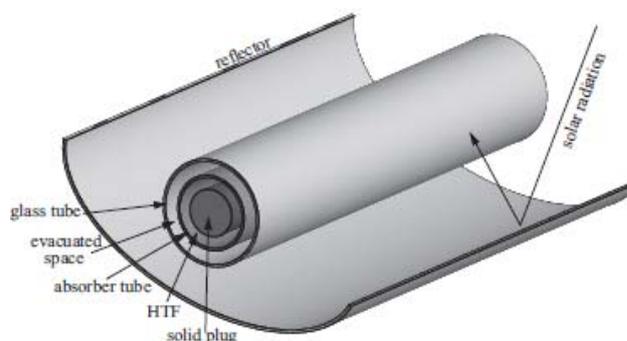


Fig. 1 Physical model of parabolic trough solar collector

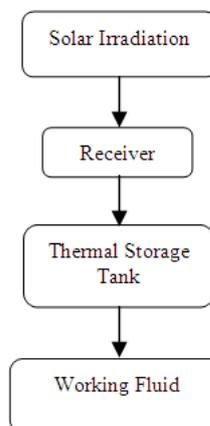


Fig. 2 Methodology of energy transfer [5]

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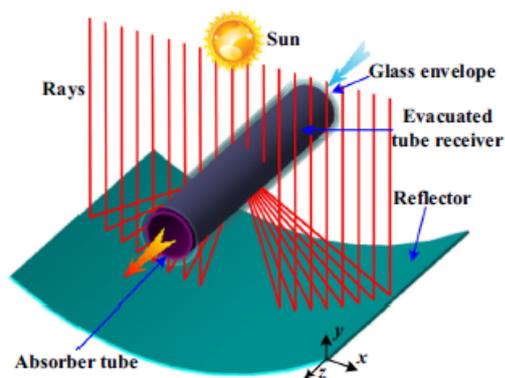


Fig. 3 Diagrammatic illustration of energy transfer process in PTC

III. CONCENTRATOR

The efficiency of the parabolic trough gets decreased by 28.29% with increasing water temperature at 106 °C and the water is fully converted into steam, whereas 53.4% efficiency is obtained with a maximum temperature of 104 °C [8]. Poly vinyl chloride concentrator with aperture area of 0.92 m² produces high reflectivity of 0.85 with overall thermal efficiency as 30.77% and water temperature of 85 °C [9]. Parabolic trough solar collectors are reviewed with different types of mathematical models, simulation and numerical methods, based on the experimental set ups with the parameters of heat loss, environmental conditions, temperature, and heat flux [10]. Different types of concentrating type collectors are used for the analysis of the performance of process heat generation such as Compound Parabolic Collector [CPC], Linear Fresnel Collector [LFC] and PTC. CPC is recommended for thermal applications between the temperatures of 373 and 423 K with the Levelized Cost of Energy [LCOE] ranging between 2.5 and 16.9 kWh/m². The differences between the LCOE values of the CPC and LFC collectors decrease with increasing working fluid temperature. Moreover LFC technology gives the lowest LCOE values when it reaches temperature of 523 K [11].

The overall efficiency of the cylindrical parabolic trough system is obtained as 71% which is best suited for solar thermal applications but the average efficiency is 66% [12]. CPC is formed of single junction Gallium Arsenide [GaAs] solar cells which generate electricity simultaneously and high temperature thermal power. The GaAs cells generate electricity from high energy photons with production of a maximum temperature up to 365 °C. Thermal efficiency is of 37% whereas electric efficiency is of 8% [13]. Total radiation of the collector is measured with respect to the various parameters such as ambient temperature, wind speed, flow rate and water inlet and outlet temperature. The high solar intensity helps in obtaining a maximum temperature of 103 °C with 98% thermal efficiency, where the minimum temperature obtained is 60 °C with 63% thermal efficiency. Steam is produced at 103 °C of outlet temperature for the thermal efficiency of 83% with heat gain of 1500 w [14].

IV. REFLECTOR MATERIAL

Aluminum composite panel reflector offers high performance with a maximum temperature of 87 °C due to high reflectivity. The chrome plate reflector with glass cover produces fluid temperature of 98 °C while it is 82 °C for the same reflector without a glass cover. Aluminum composite panel reflector has better performance due to high reflection range. Fig. 4 illustrates the efficiency levels of a chrome plate reflector and composite aluminum [4]. Low cost PTC is made with acrylic sheet as a reflector and copper receiver pipe with a rim angle of 45° and aperture area of 2.14 m². The maximum thermal efficiency and water temperature obtained are 52.35% and 80 °C respectively with a temperature difference of 47 °C [15]. Stainless steel reflector is used for the analysis of the PTC with GI absorber tube [16]. Thermal analysis of PTC is performed for the application of water heating. Two different materials are used for the analysis of the efficiency. These are copper and aluminum tubes with covered glass. Copper tube with glass covered gives the maximum outlet water temperature as 68.7 °C, whereas an aluminum tube with glass cover produces maximum water temperature of 62.4 °C. Aluminum tube produces lower efficiency than copper tube [17].

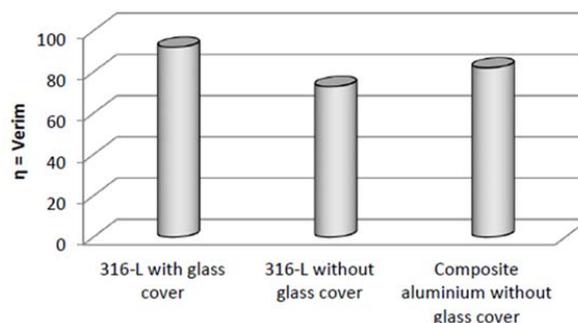


Fig. 4 Efficiency of the Collector

Performance evaluation of PTC with an aluminum sheet as a reflector for heating water which is coupled with manual tracking system was analysed. It is a better option during winter season as it reduces the cost of water heating [18]. Year-round performance is analyzed with an aluminum sheet as a reflector of a PTC for different climatic conditions. It was carried out with non-evacuated receiver tube with black paint coating and enveloped with glass cover. Maximum water temperature is noticed in April with the mass flow rate of 0.010 kg/s and aperture area of around 1.34 m² [19]. To investigate the performance of PTC two different types of reflectors were used such as aluminum sheet and aluminum foil with respect to the obtained maximum temperature [3].

V. CONFIGURATION OF ABSORBER

A single tube absorber and modified absorber are used to recover a heat from solar source. A modified absorber has efficiency of 42.1% while conventional absorber it is only of 26.7% [20]. The impact of absorber has been investigated with a nail twisted tape with twisted ratio such as 2.0 and 3.0 using

Al₂O₃/water nanofluid as the working fluid. The nail twisted tape absorber with nanofluids can make a significant improvement to the heat transfer performance of the solar trough collector [21]. A flat aluminium absorber with the bar-and-plate technology is used for the investigation of the performance of small linear solar concentrating collector used for the processing of heat and direct steam generation. The overall efficiency of this collector is 64% with the temperature of 160 K [22].

An absorber tube with pin fin insert is investigated for enhancement of the heat transfer to the medium using Monte Carlo ray tracing method along with FVM and the results are compared with the experimental results. The error seen is not more than 5%. There is an increase in the efficiency of the system after the insertion of a pin fin through increase of the overall heat transfer rate of up to 12.0% [23]. The impact of the failure of the absorber tube is analyzed using an experimental and numerical model for three different types of tubes namely, vacuum tube, lost vacuum [air] and broken glass [bare] tube. Heat losses get a significant reduction while using a vacuum tube in comparison with others [24]. Thermal efficiency of 65-70% can be achieved with an evacuated receiver which is 10% higher than for a non-evacuated receiver as a result of the improvement of heat transfer rate by decreasing the thermal boundary layer thickness [25]. Thermal efficiency of 55.2% is obtained with evacuated unshielded receiver and 53.8% of thermal efficiency was obtained with shielded evacuated receiver for low temperature application [26].

VI. WORKING FLUID

Effects arising from different volume fractions of water-based nanofluid are analyzed using CFD. The enhancement of heat transfer shows a gradual increase with the volume fraction of nanofluid. The heat transfer rate can be increased using Al₂O₃ and CuO nanoparticle by 28% and 35% respectively [27]. The effect of changing the working fluid and Reynolds number is ascertained through sensitivity analysis. Each element of the system is modeled and analyzed using FEM and validated with the results of an experimental analysis [28]. Al₂O₃/synthetic oil nanofluid is used as heat transfer fluid and the performance of the system is analyzed using FEM with non-uniform flux distribution. The temperature gradient gets reduced and the efficiency of system is high while using Al₂O₃/synthetic oil nanofluid compared with synthetic oil nanofluid [29]. A detailed analysis of the various working fluids like pressurized water, Therminol VP-1, nitrate molten salt, liquid sodium, air, carbon dioxide and helium is made between temperatures of 300 K and 1300 K. Liquid sodium produces maximum efficiency of 47.48% with inlet temperature of 800 K, when compared with other fluids. Moreover water is the best working fluid for temperature up to 550 K while helium and carbon dioxide are the best working fluids for the application of above 1100 K [30]. The parabolic system with nanofluid as a fluid is studied using CFD and experimentally validated. The maximum relative error noted is 0.3% and 7.3%, an increase of 10% on the collector efficiency

is seen with Al₂O₃ concentration of 4% [6]. Supercritical CO₂ as a heat exchanger of the parabolic trough system was analyzed with non-uniform solar flux.

Thermal performance is predicted for PTC with fluctuating solar radiation due to radiant heat loss and exit temperature of medium. The working fluid temperature shows an increase when the radiant heat surface area is small [31]. The PTC was evaluated using different heat transfer medium namely water and SAE20W50 engine oil. It can operate at a high temperature using SAE20W50 engine oil as working medium. But the performance of the collector gets reduced when compared with water as working medium [32]. An experimental study of the PTC was carried out under local weather condition using water as working medium with the maximum efficiency ranging from 65% to 70% [33]. Three types of heat transfer fluids were investigated by changing parameters including aperture area, diameter of the receiver and working fluid to optimize the design [34]. Different modes of heat transfer occur while transferring heat through the pipe. Conduction and convection modes of transfer create a major issue on the surface of receiver pipe. The heat losses that occur during testing due to the fluctuation in wind speed are maximum [35].

VII. FLOW RATE

The effect of the mass flow rate is more significant than for the water inlet temperature. The collector thermal efficiency at the finest mass flow rate is greater than the finest water inlet temperature. The highest thermal efficiency of the collector is 65%, obtained with the optimum values of input parameters [1]. Non-uniform heat flux distribution is obtained at outer surface of receiver tube because of the structure and the thermal stress distribution in the steel tube was found with the help of numerical methods [36].

An analysis of the performance of PTC was made for three different flow rates of 30 Kg/hr, 42 Kg/hr and 60 Kg/hr with the influencing parameters such as concentration ratio, optical efficiency and thermal efficiency. With the passage of time, solar intensity level gets increased followed by an increase in the thermal efficiency of collector. The efficiency decreases as solar intensity decreases. The total heat availability, heat available at collector, heat gained by water and thermal efficiency were found to be 2349.54 KJ/hr-m², 3618.29 KJ/hr, 1758.12 KJ/hr and 48.58% respectively for the flow rate of 42 Kg/hr [37]. Year-round performance analysis of parabolic trough was calculated. In April, a maximum of 12.2 °C was obtained for the mass flow rate of 0.010 kg/s with aperture area of around 1.34 m² on horizontal and inclined planes. The ultimate production of heat and optical efficiency was compared for both planes during April and May [19].

VIII. PERFORMANCE ANALYSIS

FEM was used for the analysis of the mechanical properties of the structure of a six meter long PTC. Variations in temperature with a mass flow rate and thermal efficiency were computed. The maximum temperature obtained was 123 °C at

a pressure of 2 bars for the maximum efficiency of 22.4% [38]. Investigation of the thermal and optical efficiency of the PTC was done with the simulation tool which simulates using the FEM for different operating conditions. The maximum optical efficiency obtained was 75% for high temperature level when the concentration ratio is at 45° from vertical direction at the same time Reynolds number varies due to the water inlet temperature. At low temperature, the flow would be laminar with the convection coefficient of about $300 \text{ W/m}^2 \text{ K}$, the flow is turbulent at high temperature with the convection coefficient of $1000 \text{ W/m}^2 \text{ K}$ [39].

The effect of wind load, heat loss, type of collector and receiver tubes were investigated. The PTC resists the aerodynamic forces caused by the wind, and the airflow around the receiver tube. The system was investigated with three different trough geometries by varying the focal length of the parabola, i.e. the depth of the trough. The aerodynamic force on the trough also increases with increase in the depth of the parabola which causes a maximum temperature difference between the receiver and the ambient air. While the aerodynamic load on the trough reduces significantly due to increase in the yaw angle, the heat flux around the receiver tube shows a slight decrease [40].

The performance has been investigated under condition of direct normal solar irradiance (DNI) based on energy balance equations and a thermodynamic analysis. Different control volume methodologies have been used for modelling the solar irradiance based on the time intervals of the data acquisition system to eliminate errors arising from the fluctuations of the outlet temperature and DNI [41]. A mathematical model has been made for finding the optical efficiency of the parabolic trough solar collector in three typical regions of solar thermal utilization. The performance characteristics were calculated based on cosine effect, shadowing effect, end loss effect. Optical efficiency was calculated and simulated for 365 days. Changes in optical efficiency of PTCs from 0.4 to 0.8 were noticed. The maximum optical efficiency was obtained in June and the minimum during December [42].

IX. TRACKING MECHANISM

FEM has been developed for the analysis of the capability of torsion and bending forces on the support frame under dead and wind load with an aluminum and mirror collector. The efficiency of aluminum was found to be 8% lower than for the mirror reflector under dry weather condition with micro controller automated tracking mechanism [43]. Various collector positions have been analyzed using a refrigerant for the tracking system [44]. The circumferential flux distribution on absorber tubes was simulated using the coordinate transformation and MCRT method. The installation error in X direction was 0.2% while in Y direction it was 1.0% to 0.5% with the geometric concentration ratio of 20 and 90 rim angle and tracking error would be 4 mrad. As the incident angle increases, the error becomes larger. The error become smaller as concentration ratio is increased [45].

The performance of PTC has been enhanced through variations in fluid flow, increasing fluid temperature and

incident solar radiation with and without an absence of tracking mechanism. Compared to without engaging tracking system, 27% efficiency has been achieved when using system with tracking mechanism [46]. A detailed two dimensional numerical heat transfer analysis was performed for the PTC system under local climatic conditions by dividing the receiver into many control volumes along the length with the consideration of all modes of heat transfer. Tracking system provided 96% efficiency while it was in the direction of polar east-west and 94% in the direction of horizontal east-west tracking [47]. Optical properties of reflector and absorbing materials were analyzed for different materials instead of analyzing performance of concentrating collector.

X. APPLICATIONS

PTC used for cooking applications produces a high temperature with 36 m^2 of reflective area. It can produce 84566 Kcal/day from 6 parabolic troughs with 60% collector efficiency. This energy is enough to prepare 3 meals 3 times for 250 people [5]. Energy analysis and comprehensive energy of the system were analyzed to determine the performance characteristics of the process. In this system, 85.85 kWh/day energy consumption was made with present system while the energy consumption of the proposed system was found to be 1.235 kWh; by this, 98.56% energy saving can be achieved for the payback period of 8.5 years [48].

Maximum of 76% optical efficiency and 70.5% thermal efficiency were obtained while operating the system with molten salt between the temperatures of 300°C and 500°C [49]. The efficiency of various thermal power plants was validated to analyze the working efficiency of PTC. A maximum deviation of 3.1% and 3.6% occurred between Gurgaon and Rajasthan power plants. A model has been developed and the performance was validated with various power plants to analyze. Variations from 0.4% to 13.7% were seen with an average deviation of 6.8% [50]. The stability of the cooling system was analysed with the considerations of solar collector and storage tank dimensions in the ammonia-water absorption cooling system [51].

XI. CONCLUSION

The thermal performance of PTC was analyzed which showed variations depending on the parameter and utilization of radiation level. The outlet temperature of the medium showed increase or decrease through changes in the concentrating ratio of the reflector and properties of the absorber tube, the utilization of the solar radiation has been different for different areas so the overall performance changed for the same system at different locations. Most of the PTC was used for the production of electricity while it was just the minimum when used for other applications. The overall efficiency of the PTC depends on reflector, absorber tube and working medium but can attain maximum efficiency when the system was engaged with solar tracking mechanism to utilize maximum radiation of the sun.

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