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Research paper

Experimental and simulation studies of parabolic trough collector design for obtaining solar energy

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Abstract

Concentrated solar power has great potential for large scale renewable energy sources, and is currently an eye catching one for its utilization with wide area of improvement. Especially, parabolic trough solar collectors (PTSCs) are gaining popularity due to their increased efficiency as compared to photovoltaics. In this work, an effort has been made to evaluate the performance of a designed 5-m length PTSC model. Heat collecting element was made of stainless steel with water as working fluid. The authentication of the proposed model is justified based on the results obtained on a yearly scale with respect to average inlet and outlet temperatures, surface temperatures and thermal efficiency for the climatic conditions of Ramanagaram. It was observed that March to May yielded better outlet temperatures ranging from 93 °C to 103 °C. Experiments were carried out at different flow rates of 0.4 LPM, 0.8 LPM and 1.2 LPM and corresponding Reynolds number was calculated. It was seen that February to May gave good surface and outlet temperatures as compared with other months while the liquid flow is laminar. Simulation studies were carried out using ANSYS software on receiver tube to ensure the robustness and design effectiveness under static loading conditions.

Keywords: Parabolic trough solar collector; Receiver tube; Solar thermal; Static structural analysis

1. Introduction

One of the most important roles in providing clean non-polluting energy in domestic and industrial applications is played by solar thermal systems. Concentrating solar technologies, such as parabolic dish, compound parabolic collector and parabolic trough, have the ability to operate at high temperatures and are used to supply heat to the industrial process, off-grid electricity and huge electrical power. In a parabolic trough solar collector (PTSC), the reflective profile focuses sunlight on a linear receiver tube or heat collecting element (HCE) through which heat transfer fluid is pumped. This fluid collects the solar energy in the form of heat that can then be used in various applications. Key components of PTSC include the collector structure, the receiver or HCE, the drive system and the fluid circulation system, which conveys thermal energy to its point of use.

The use of concentrating solar energy collectors dates back to the late 19th century. The technology was originally used for pumping water although more unusual applications included a steam-powered printing press demonstrated at the1902 Paris Exposition [1]. It was not until the mid-1970s when large-scale development of PTSCs began in the United States under the Energy Research and Development Administration (ERDA), later the Department of Energy (DOE) (U.S. Department of Energy, 2004). This development was strongly influenced by geopolitical factors, such as the oil crisis, and focused on the provision of industrial process heat rather than electrical power. Typical applications of trough technology included laundry processing, oil refining and steam production for sterilization of medical instruments [2]. The first trough-based Solar Electric Generating Systems (SEGS I) power plant was constructed in 1984 in the U.S. state of California. Eight further plants followed, the last being completed in 1991. Together, SEGS I–IX represent a total of 354 MW of installed electrical capacity and all the plants are still operational. A tenth plant was planned but

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abandoned when the development company failed to secure financing for construction and went bankrupt (U.S. Department of Energy, 2004). Cheap and stable oil supplies through the 1980s meant no new parabolic trough power.

In recent years, a new momentum in PTSC research has developed, fueled by climate concerns, dwindling oil reserves and political instability in some oil-producing countries. An attractive feature of the technology is that parabolic trough solar collectors are already in use in abundant numbers and research output is likely to find immediate application. Parabolic trough technology has made the crucial leap from pure concept to working solution, offering a real alternative to fossil fuel energy sources. This demonstrated capability gives credibility to trough research, which is now focused on ways to advance PTSC technology and reduce the costs of constructing and operating trough-based power plants.

In the year 2010, Fernandez-Garcia et al. presented an overview of the parabolic trough solar collectors that have been built and marketed in the past century along with a prototype of PTSC under development. It also presents a survey of systems which could integrate this type of concentrating solar system to supply thermal energy up to 400 °C, mainly steam power cycles for electricity generation, as well as examples of each application [3].

A model of trough collector considering new ideas was built using MCNT/mineral oil nanofluid as working fluid with different types of receiver tubes as a significant increase of 11% was achieved on the efficiency of the designed model [4]. Another approach to improve the efficiency was attempted by using molten salt as working fluid [5]. A heat transfer medium with a melting point of 86 °C and a working temperature upper limit of 550 °C was employed. The results depicted that the total heat transfer coefficient of the water to salt heat exchanger ranged between 600 and 1200 W/(m^2-K) for $10{,}000 < Re < 21{,}000$ and $9.5 < Pr < 12.2$. The comparative analysis between the experimental results and empirical correlations demonstrated good performance of low melting point molten salts. In recent studies, Sylthern 800/Al_2O_3 nanofluid was used as working fluid, and a boost of up to 10% on the collector efficiency was observed for an Al_2O_3 concentration of 4% [6].

Experimental characterization of solar parabolic trough collector used in micro-cogeneration systems was carried out. The system produces saturated steam during 8 hrs with a quality higher than 0.6 for a flow rate of 33 kg/hr. The dynamics of the collectors were observed on a cloudy day under two-phase flow, slow strong variations of the output power and flow rate that can even cease with clouds [7].

A comprehensive thermo-optical modeling was proposed to evaluate the performance of a small SPTC with different heat equilibriums in the environment. The developed model is estimated to have a year-round performance assessment with respect to water temperature rise, heat energy generations, optical and thermal efficiencies for climatic conditions of Bhiwani, India [8]. A thermodynamic model framework for low enthalpy process was simulated for SPTC [9]. The simulation results show that in the presence of twisted tape insert, the Nusselt number, the removal factor, the friction factor and the thermal efficiency increase with respect to the empty tube as both twisted ratio and Reynolds number decrease. It was also observed that the enhancement in energy is achieved only when augmentation entropy generation number $N_{s,a} < 1$. If $N_{s,a} > 1$, it is not advisable to use twisted tape insert. In order to facilitate the investigators in the field of parabolic trough solar collector technologies and to highlight the applications such as air heating systems, desalination, industrial purposes and power plants, etc. and their future perspective, a review was carried out which focused on the performance and efficiency of the system [10].

For researchers interested in contributing to the development of PTSCs it is important to be able to test new collector components. To this end, the construction of a parabolic trough collector is vital and a number of such PTSCs have been constructed for research institutions, ranging in size from 1 m^2 to 100 m^2. Smaller-scale PTSCs can be used to test improvements in receiver design, reflective materials, control methods, structural design, thermal storage, testing and tracking methods [11]. One such PTSC with an aperture area of 7.5 m^2 has been developed.

The aim of this study is to test the newly developed PTSC and characterize its performance. This is to be done using a suitable solar collector test standard and comparing the results with a thermal model of the PTSC. The results of this study will allow the performance of new parabolic trough components such as heat collecting elements and surface materials to be measured when the collector becomes a test-rig in an ongoing solar thermal research program.

2. Description of test apparatus

The equipment tested in this study is composed of a locally developed parabolic trough solar collector. The PTSC has a torque-tube structure with a length of 5 m and an aperture width of 1.5 m making a rim angle of 82.2° (Fig. 1). The reflective surface is made of stainless steel sheets covered with aluminized silver reflective film and clamped into the profile formed by parabolic ribs.

Heat collecting element or receiver tube used for testing was made of stainless steel with a diameter of 0.508 m and a length of 5 m to carry the working fluid. The working fluid used was water (Fig. 2).

Table 1 summarizes the key parameters of the parabolic trough solar collector.

The working fluid used is water [12]. 1000 L overhead tank is used to create the potential. A test flow rate of 0.4–1.2 LPM was used to ensure turbulent conditions in the receiver throughout the expected temperature range. Fluid density fluctuations were accommodated during data processing using the water temperature to calculate mass flow rate for each datum point. During testing, flow meter readings were checked by physical measurement. Small variations in mass flow rate were allowed between low and high temperature tests, but properly accounted for in the processing of test data [13].

3. Construction of parabolic trough collector

The development of PTSCs by institutes and universities for research purposes is well documented in the literature. For

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