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Techno-economic performance analysis of parabolic trough collector in Dhahran, Saudi Arabia

Esmail M.A. Mokheimer *, Yousef N. Dabwan, Mohamed A. Habib, Syed A.M. Said, Fahad A. Al-Sulaiman

Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia

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ABSTRACT

The main criteria to assess a new solar thermal power plant are its performance and cost. Therefore, there is a need to present to the open literature a detailed modeling procedure and cost analyses to help researchers, engineers, and decision makers. The main objectives of this work are to develop a code and to evaluate the optical and thermal efficiencies of parabolic trough collectors (PTCs) solar field considering average hourly, daily, monthly, or annually averaged weather data; in addition to detailed cost analysis of the solar field. In this regard, a computer simulation code was developed using Engineering Equations Solver (EES). This simulation code was validated against Thermoflex code and data previously published in the public literature, and excellent agreements ware observed. The types of the PTC considered in the simulation are EuroTrough solar collector (ET-100) and for LUZ solar collector LS-3. The present study revealed that the maximum optical efficiency that can be reached in Dhahran is 73.5%, whereas the minimum optical efficiency is 61%. This study showed also that the specific cost for a PTC field per unit aperture area and the specific cost of different mechanical works can be cut by about 46% and 48% at 10 hectare and by about 72% and 75% at 160 hectare, respectively, compared to that at 2.8 hectare. On the other hand, the specific civil costs remain constant independent of the plant size. It was found that the ratio of the cost of the PTC to the solar field area decreases significantly as the solar field size increases. This decrement is very significant until the solar field size reaches 60 hectare and then the slope of the decrement is becoming insignificant. Therefore, it is recommended to have a solar field size of 60 hectare or larger.

1. Introduction

The main four concentrating solar thermal power technologies are parabolic trough collectors, Fresnel reflector, solar tower, and dishes. Parabolic trough collector (PTC) currently represents the most mature technology for solar thermal power production among them. The first commercial power plant using PTC technology was built in 1984 in California. Currently, several power plants under operation and many others under construction. However, there is no study reported the optical and thermal efficiencies or the economics of using parabolic troughs under Saudi weather conditions where solar energy is abundant. Thus, parabolic trough CSP technology has been selected for the present thermo-economic study. Performance and cost analyses are the two main criteria in selecting a power plant technology type and therefore there is a need to have clear method that shows how to model and analyze a plant. Given the importance of the heat transfer analysis in PTC system, since the 1970s a number of models has been proposed.

Edenburn [1] predicted the efficiency of a parabolic trough collector by using an analytical heat transfer model for evacuated and non-evacuated cases. The results showed good agreement with measured data obtained from Sandia National Laboratories (SNL) collector test facility [2]. Clark [3] identified and analyzed the effects of design and manufacturing factors that influenced the thermal and economic performance of PTC. Dudley et al. [4] developed an analytical model of SEGS LS-2 parabolic trough collector. The thermal loss model for the heat collection element (HCE) was one-dimensional and steady-state heat transfer model based on thermal resistance analysis. This model was validated with experimental data collected by SNL[2] for two types of receiver selective coatings combined with three different receiver configurations; glass envelope with either vacuum or air in the receiver annulus, and glass envelope removed from the receiver. The results showed a reasonable agreement between the theoretical and experimental heat losses. Thomas and Thomas [5] developed a

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* Corresponding author. Address: Mechanical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), P.O. Box: 279, Dhahran 31261, Saudi Arabia.

E-mail address: esmailm@kfupm.edu.sa (E.M.A. Mokheimer).

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Nomenclature

ANI	aperture normal irradiance
A_a	aperture area
Ar	receiver area
A_{ir}	inside cross sectional area of the absorber tube
C_P	specific heat
D_{ci}	inner diameter of glass envelope
D_{co}	outer diameter of glass envelope
D_i	inner diameter of absorber tube
DNI	direct normal irradiance
D_o	outer diameter of absorber tube
E	equation time
$f_{end\ loss}$	performance factor that accounts for losses from ends of heat collector element
f_{clean}	cleanliness factor
$f_{row\ shadow}$	performance factor that accounts for mutual shading of parallel collector rows during early morning and late evening
F'	collector efficiency factor
F''	collector flow factor
f_2	friction factor for the inner surface of the absorber pipe
f_n	focal length of the collectors
F_R	collector heat removal factor
h_{fi}	heat transfer coefficient inside tube
h_w	wind heat transfer coefficient
IAM	incidence angle modifier
k_c	thermal conductivity of the glass envelope
L	collector length
L_{loc}	the longitude of the location of the collector site
L_{st}	standard meridian for the local time zone
L_{space}	distance between two parallel collectors
L_{SCA}	length of a single solar collector
n	the day number of the year
P_r	Prandtl number
Q_{abs}	solar radiation absorbed by the receiver tubes
Q_u	net energy transferred to the fluid in receiver tubes
r	local mirror radius
T_a	ambient temperature
T_i	absorber inner surface temperature
T_{co}	outer glass envelope temperature
T_{ci}	inner temperature of glass envelope
T_{fi}	fluid temperature at inlet of receiver
T_{fm}	main fluid temperature
T_{oi}	fluid temperature at outlet of receiver.
T_{sky}	sky temperature
U_L	receiver loss coefficient based on the receiver outside surface area
U_o	receiver overall heat transfer coefficient based on the receiver outside tube diameter
V_f	velocity of HTF inside the tube
W_a	parabola's aperture width

Greek letters

α_c	absorptance of the absorber surface coating
$(\tau\alpha_c)_n$	the effective product of τ and α_c
γ	intercept factor
σ	Stefan–Boltzman constant.
$\varnothing$	latitude location of the solar field.
μ	absolute viscosity for heat transfer fluid.
$\eta_{nominal}$	nominal optical efficiency
η_{opt}	optical efficiency
$\eta_{th,collector}$	thermal collector efficiency
θ	angle of incidence
θ_z	zenith angle
ρ_{cl}	clean mirror reflectivity
ρ_f	density for heat transfer fluid
τ	transmittance of the glass envelope
ε_{ci}	emittance of glass envelope inner surface
ε_{co}	emittance of glass envelope outer surface
ε_r	emittance of the receiver

set of curve-fitting equations based on a numerical heat transfer model for the heat losses in the HCE of a PTC for different properties of the HCE and weather conditions. A detailed heat transfer model for the HCE of PTC was developed by Forristall [6]. Both one- and two-dimensional analyses were used in the code. This model was used to determine the thermal performance of parabolic trough collectors under different operating conditions.

It is known that the collector outlet temperature is mainly affected by changes in the sun intensity, by the collector inlet temperature, and by the volume flow rate of the HTF. Stuetzle [7] proposed an unsteady state analysis of HCE of PTC to calculate the collector field outlet temperature. Their results showed good agreement with measured outlet temperatures. Valladares and Velásquez [8] developed a detailed numerical model for a single-pass and double-pass solar parabolic trough collector. The single-pass solar device numerical model has been validated with experimental data obtained by SNL. Their results showed that the proposed double-pass could enhance the thermal efficiency compared with the single-pass. Recently, three dimensional heat transfer analysis of PTC system was performed by combining the Monte Carlo Ray Trace Method (MCRT) and CFD analysis [9,10]. The results indicated that the flange (support bracket) and bellow under non-vacuum conditions bring a high conductive heat loss.

Lobón et al. [11] performed CFD simulation of parabolic trough solar collector considering steam as a heat transfer fluid using STAR-CCM+ code. However, such a code does not consider several parameters that are function of solar time variation. In a different study, Ceylan and Ergun [12] conducted thermodynamic analysis of temperature controlled parabolic trough collector. Nevertheless, their analysis did not consider the optical performance and solar time variation. Ouagued et al. [13] presented a thermal model of parabolic trough solar collector considering Algeria weather conditions. However, they have ignored some of the optical performance parameters and their study did not consider any cost analysis.

It can be noticed from the literature review that there is no detailed thermal model that presents the detailed performance of the PTC considering complete set of variables that affect the performance. The model developed in this study considers several key PTC performance parameters, such as:

- angle of incidence and angle of incidence modifier,
- heat end losses of the heat collector element,
- cleanliness factor, row shadowing,
- day number of the year,
- zenith angle,
- focal length of the collectors,
- aperture normal irradiance,
- collector flow factor,
- velocity of the Heat Transfer Fluid (HTF) inside the tube, and
- friction factor of the absorber inner surface.

Therefore, the developed model considers a complete modeling of PTC and it will be a key for researchers and engineers in the area. The present model was developed in EES and validated with