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Thermo-mathematical modeling of parabolic trough collector

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ABSTRACT

A comprehensive thermo-mathematical analysis for parabolic trough solar collector (PTSC) was completely performed in this study. Based on actual system parameters, solar, optical and thermal models were developed by using differential and non-linear algebraic correlations. Obtained solutions for the differential equations were integrated into Engineering Equation Solver (EES) and solved simultaneously with the all model equations. The developed model was compared to the experimental data of Sandia National Laboratory (SNL) and yielded satisfactory results showing a pretty good consistency with respect to the other model studies. Finally, the current model was applied to an existing PTSC module to analyze the performance characteristics under different operating conditions.

1. Introduction

In recent years parabolic trough solar collectors have gathered much more interest since they have remarkable advantages with respect to the stationary solar thermal technologies such as relatively high thermal performance and operating temperature. Such typical characteristics put them forward to be used in industrial process heat (IPH) and concentrating solar power (CSP) applications. There are currently several commercial PTSCs for CSP plants that have been successfully tested in a temperature range of 300–400 °C. A number of projects for solar electric generating systems (SEGS) are currently under development or construction worldwide. Up to date, there are 20 active parabolic trough power plants, and 27 parabolic trough power plants are being constructed [1]. New SEGS plants concentrate on substantial technological progress in vacuum technology, selective surfaces, manufacturing processes, and improved materials. Additionally; a number of works have been carried out for reducing the cost of energy using advanced thermal energy storage techniques (such as storage in concrete medium and thermocline tanks), and for overwhelming the limitations originated from the heat transfer fluid used. The heat transfer fluid is usually synthetic oil or molten salts. The synthetic oil is the most common solution in spite of its flammability, toxicity, and chemical instability characteristics, as well as its relatively low operating temperature (<400 °C). On the other hand, the molten salts allow increasing the maximum working temperature up to 550 °C however they require anti-freezing systems due to their solidification temperature of about 250 °C. Recent works on transparent receivers combined with gas-based nanofluids are investigated for high temperature applications i.e. 650 °C to overcome the above-described limitations [2]. Although most of the PTSC applications focus on CSP, IPH applications have also been gaining momentum in the course of time. In 2007, there were about 90 number of operating IPH solar thermal plants worldwide (China and Japan not included) with a total capacity of about 25 MWth [3]. Approximately 45–65% of the total energy is used for direct application of industrial process heat in the preparation and treatment of goods. The thermal energy demand for IPH is below 300 °C, and 37.2% of the total demand is in the range of 92–204 °C. According to the ECOHEATCOOL study done in 32 countries, 27% of the thermal energy demand for IPH is between 100 and 400 °C [4].

Along with increasing IPH and CSP applications, necessarily have increased the researches on the PTSCs and their analyses. However, the thermal and/or mathematical analyses have been developed with either simplified approaches for a specified system [5,6] or more detailed ones. Simplified approaches save considerable time of the analyst but they may not provide constantly to get consistent solutions particularly when the number of variables is high. On the contrary, more comprehensive and realistic analyses make possible to obtain more accurate results reflecting the nearest system characteristics of the PTSC. Thus making a detailed analysis shows the effective system parameters on the performance of the PTSC and provides us to apply it to the fronting studies relevant with thermal system design.

Many researchers presented energy models on parabolic trough collectors. When the studies conducted on detailed modeling of

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Nomenclature

A	cross-sectional area, m^2
C	concentration ratio
c_p	specific heat capacity, J/kg °C
D	diameter, m
f	focal distance, m; friction factor
F	view factor
F_R	heat removal factor
h	convection heat transfer coefficient, W/m^2 °C
I_b	beam radiation, W/m^2
J	radiosity, W/m^2
k	thermal conductivity, W/m °C
K	extinction coefficient, m^{-1}
Kn	Knudsen number
k_{eff}	effective thermal conductivity, W/m °C
k_{std}	thermal conductivity of annulus gas at standard condition, W/m °C
L	thickness of glass cover, m
l_a	parabola length, m
L_c	characteristic length, m
M_g	molecular weight of gas, kg/mol
M_s	molecular weight of solid, kg/mol
$\dot{m}$	mass flow-rate, kg/s
n	refractive index
Nu	Nusselt number
p	perimeter, m
Pr	Prandtl number
$\dot{Q}$	rate of heat transfer, W
$\dot{Q}_u$	useful energy gain, W
Re	Reynolds number
Ra	Rayleigh number
r_r	rim radius, m
$r_\perp$	perpendicular component of unpolarized radiation
$r_\parallel$	parallel component of unpolarized radiation
S	curve length of parabola, m; absorbed solar energy, W/m^2
T	temperature, °C
T_a	ambient temperature, °C
T_{bulk}	bulk mean fluid temperature, °C
T_{ex}	exit temperature, °C
T_f	film temperature, °C
T_{in}	inlet temperature, °C
U_L	thermal loss coefficient, W/m^2 °C
u_m	mean velocity, m/s
w_a	parabola aperture, m

Greek letters

α	absorptivity
α_n	normal absorptivity
γ	intercept factor; specific heat ratio
Γ	end-effect
δ	declination angle, deg
ε	emissivity
ε'	miscellaneous factor
ζ	shading factor
η_o	optical efficiency
η_{PTC}	efficiency of parabolic trough collector
θ	incidence angle, deg
θ_z	zenith angle, deg
κ	end-effect correction
λ	wavelength,
ρ	reflectance of parabolic mirror; density, kg/m^3
σ	total reflected-energy standard deviations at normal incidence, rad
τ	transmissivity
φ_r	rim angle, °
ϕ	latitude, °
ω	hour angle, °

Subscripts

1; 2	medium number
a	absorber
ac	between absorber and cover
air	ambient air
an	annulus
c	cover
cond	conduction
conv	convection
HTF	heat transfer fluid
ia	inside of absorber
ic	inside of cover
oa	outside of absorber
oc	outside of cover
rad	radiation
r	retainer
sky	sky

Abbreviations

CSP	concentrating solar power
EES	Engineering Equation Solver
HTF	heat transfer fluid
IPH	industrial process heat
PTSC	parabolic trough solar collector
RMSE	root mean square error
SEGS	solar electric generating systems
SNL	Sandia National Laboratory

PTSC are handled, Edenburn [7] predicted the efficiency of a PTC by using analytical methods for heat transfer modeling for evacuated and non-evacuated annulus. The results showed good agreement with data measured from SNL collector test facility. Kalogirou [8] studied the performance characteristics of the parabolic trough collector system and its analytical model equations. Odeh et al. [9] developed a simulation to evaluate the efficiency and the thermal losses of parabolic trough collectors for the case of synthetic oil and water usage. The most noticeable and broad models were established by Forristall [10] who developed both one-dimensional and two-dimensional heat transfer models of parabolic trough solar receiver implementing in Engineering Equation Solver (EES) and compared the models. The results indicated that the two-dimensional model provides a higher degree of accuracy than the one-dimensional model when evaluating long receivers greater than 100 m. Moreover, he investigated the effects of many collector parameters on the collector efficiency. The other study is of Jacobson et al. [11] who developed a solar parabolic trough simulation to determine the optimum parameters to sustain a solar thermal power plant system in Thailand. Garcia-Valladares and Velazquez [12] carried out detailed numerical simulations for thermal and fluid-dynamic behavior of single-pass and double-pass solar parabolic trough collectors. Another study was made by Qu et al. [13] who applied a model to the tubular receiver to improve the PTSC design and overall system performance. The model was verified by the experimental data taken from the tests of the PTSC system which was used for high temperature solar cooling and heating. Padilla et al. [14] performed a one-dimensional numerical heat transfer analysis, and an optical analysis to optimize the PTSC and understand its performance under different operating conditions. In order