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Modeling, simulation and performance analysis of parabolic trough solar collectors: A comprehensive review

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HIGHLIGHTS

- Current and past studies on modeling of parabolic trough collector are presented.
- Optical and thermal models and the modeling approaches are discussed in detail.
- Analytic and ray-tracing approaches are investigated for optical modeling.
- Steady and transient heat transfer conditions are examined for thermal modeling.
- Novel, passive and nanofluid techniques are outlined in performance enhancement.

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ABSTRACT

Solar thermal systems are advantageous since it is easier to store heat than electricity on a large scale. As such, concentrated solar power is receiving considerable interest among researchers, developers and governments. Several concentrated solar power technologies have been developed including the solar tower, the parabolic trough technology, solar dish and linear Fresnel systems. Among them, the parabolic trough solar collector is a proven technology used dominantly for both industrial process heat and power generation. This technology has matured over the years, and its advancement has become the topic of numerous research studies which were the counter driving force of the field. Particularly in recent years, a significant amount of theoretical and numerical studies have been conducted to assess and improve the performance of parabolic trough solar collectors. This review methodologically holds colossal knowledge of current and past studies to assess the optical and thermal performances of parabolic trough solar collectors, modeling approaches and the potential improvements proposed on behalf of the parabolic trough solar collector design. The optical modeling approaches are identified to be analytical and ray-tracing. The review of thermal modeling approaches presents the steady and transient heat transfer analyses of single and two-phase (with direct steam generation) flows. Also, the computational fluid dynamics models used to analyze the physics of parabolic trough solar collectors with a better insight are reviewed and presented. Finally, the studies conducted on the performance improvement of parabolic trough solar collectors are separately examined and presented, these include novel designs, passive heat transfer enhancement, and nanoparticle laden flows.

1. Introduction

Solar energy is the world's most abundant source of energy, it has been shown to have significant potential to meet a considerable portion of the world's energy demand [1,2]. With 1.7 × 10^{14} kW of the sun's energy received by the earth surface, only 84 min of solar radiation was estimated to give 900 EJ which was equivalent to the world's energy demand for 2009 [1]. However, significant research and development efforts are still needed to overcome challenges associated with harnessing this resource [3]. These include developing efficient technologies for harvesting, cost effective and efficient energy storage options, optimization of hybrid energy systems working with solar energy and another renewable energy resource.

Concentrating solar power (CSP) is an emerging technology and offers significant advantages such as built-in storage capability, high economic returns and reduced greenhouse gas emissions. The life-cycle

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Nomenclature

A	area, m^2
c, c_p	specific heat, J/kg °C
C	concentration ratio
D	diameter, m; absorber's outer diameter, m
E	total energy per unit mass, J
f	focal length, m
h	convection heat transfer coefficient, W/m^2 °C
I_b	beam radiation, W/m^2
k	thermal conductivity, W/m °C
k_{eff}	effective thermal conductivity, W/m °C
Kn	Knudsen number
l	collector length, m
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer, W
q''	heat flux, W/m^2
Ra	Rayleigh number
Re	Reynolds number
r	local mirror radius, m
r_r	rim radius, m
t	time, s
T	temperature, °C
U_L	thermal loss coefficient, W/m^2 °C
w_a	aperture width, m
x, y	cartesian coordinates

Greek symbols

α	absorptivity
Γ	end-loss factor
γ	intercept factor; surface azimuth angle, °
δ	declination angle, °
ε	emissivity
η_o	optical efficiency
θ	incidence angle, °
μ	dynamic viscosity, kg/m s
ρ	reflectivity; density, kg/m^3
σ	optical error, mrad
τ	transmissivity
$\vec{v}$	velocity vector
φ	local rim angle, °
ϕ_r	rim angle, °
φ	particle concentration, %
ω	hour angle, °

Subscripts

a	ambient air; absorber
ae	absorber envelope
conv	convection
e	envelope
f	fluid
Gauss	Gaussian distribution
htf	heat transfer fluid
ia	inside of absorber
ie	inside of envelope
nf	nanofluid
oa	outside of absorber
oe	outside of envelope
p	particle
rad	radiation
s	support
sky	sky
tot	total

Abbreviations

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
CFD	computational fluid dynamics
CSP	concentrating solar power
DARS	direct absorption receiver system
DSG	direct steam generation
FDM	finite difference method
FEM	finite element method
FVM	finite volume method
HCE	heat collector element
HTF	heat transfer fluid
IPH	industrial process heat
LCR	local concentration ratio
MCRT	Monte Carlo ray tracing
NCPTSC	nanofluid-based concentrating PTSC
PEC	performance evaluation criterion
PSA	Plataforma Solar de Almería
PTSC	parabolic trough solar collector
PV	photovoltaic
SEGS	solar energy generating systems
SNL	Sandia National Laboratories

CO_2 emissions of solar-only CSP plants are estimated to be 17 g/kWh while they are on the level of 776 g/kWh and 396 g/kWh for coal and natural gas combined plants, respectively [4]. Although the investment costs of CSP plants are relatively higher compared to the conventional technologies, new plants are guaranteeing commercial maturity, increased plant efficiency, and reduced levelized costs. With increasing installed CSP capacity, investment and energy costs are estimated to fall. The levelized costs of electricity will come to the level of US $97–130/MWh by 2015–2020 [4] from US$194/MWh [5].

The parabolic trough solar collector (PTSC) is a dominant technology available today in both commercial and industrial scale among the medium-temperature solar collectors. In comparison to other systems, Fig. 1 shows the temperature ranges of commonly used solar thermal systems [1]. Numerous manufacturing companies have focused on this technology, Fresnel and parabolic dish technologies have become largely overshadowed. Feed-in tariffs and grant programs have driven the successful deployment of the technology, as well. Significant research and development efforts have been put into action to improve the technology and make it competitive with counterpart energy systems [6,7]. The PTSC technology has just maintained a substantial progress in mirror and receiver development, use of alternative heat

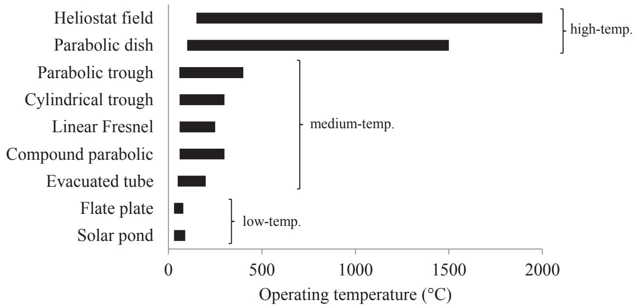

Fig. 1. Temperature ranges attainable with different solar technologies.