Solar Energy 139 (2016) 365–380

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Coupling 2D thermal and 3D optical model for performance prediction of a parabolic trough solar collector

Weidong Huang [a,*], Qian Xu [a], Peng Hu [b,*]

[a] Department of Earth and Space Science, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui 230026, China
[b] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei, Anhui 230026, China

ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 22 September 2016
Accepted 26 September 2016
Available online xxxx

Keywords:
Parabolic trough
Heat transfer model
Thermal radiation analysis
Optical model
Numerical algorithm

ABSTRACT

A 2D thermal model for tube receiver in parabolic trough solar collector is proposed, and a fast numerical algorithm is developed. Comparing to the previous models, we consider the radiation loss from the side plate of the tube receiver and direct transmission of the absorber radiation to the air to construct a physical model and mathematical equations. We also reduce the calculation by simplifying them to algebraic equations for numerical solution without needing iteration after ignoring the axial heat transfer. It is further coupled to the three-dimensional optical model to predict the performance of parabolic trough solar collector. The performances of the overall model and thermal model are tested against experimental measurements from Sandia National Laboratories. In all cases, the simulation results show a good agreement with the experimental results. The models developed in this paper can predict performance of parabolic trough solar collector with parabolic trough reflector and tube receiver accurately and quickly based on the structure and material properties of the system.

1. Introduction

The model for simulation of solar thermal performance includes the optical model for calculation of the optical performance and the thermal model for calculation of the thermal performance of parabolic trough solar collector.

For the optical model, the ray tracing code is a well-known method with high flexibility, reliability and accuracy, but it is merely used for transient simulation because of huge computation (Garcia et al., 2008; Grena, 2010). Bendt et al. propose an analytical method for performance simulation which considers almost all relevant parameters including reflectivity, absorptivity and transmittance, etc., however, an average value is calculated and applied while the variance in different moment is not taken into account (Rabl et al., 1982). Jeter presents a semifinite formulation which regards reflectivity of reflector, the transmittance and absorptivity of vacuum receiver are related to the incident angle (Jeter, 1987a), to calculate flux distribution of the collectors. The optical efficiency of the solar trough system varies dramatically with different time and day of a year. Calculating the energy collected by the system over a year is necessary in evaluating solar trough system. Recently we have developed a three-dimensional model (Huang et al., 2012) for the optical efficiency calculation of the solar concentrated system directly. First of all, the optical efficiency of a given point on the reflector is calculated, and then the optical efficiency of the whole system is calculated based on the integration to the whole reflector, which is relatively simple and fast as well as accurate. We applied this integral method to develop an optical model for simulation of performance of the solar trough system (Huang et al., 2012), dish system with sphere (Huang et al., 2013a) and cavity (Li et al., 2013) receiver, linear Fresnel system (Huang et al., 2014), fixed mirror system (Li et al., 2015), heliostat (Huang et al., 2013b) and solar tower system (Huang and Xu, 2014), the average annual performance of various solar concentrated system can be calculated accurately and quickly.

The tube receiver is commonly used as the receiver of parabolic trough solar collector to convert solar energy to heat. It is mainly composed of a stainless steel absorber with spectral selective coating surface and transparent glass envelope outside the absorber, solar energy is absorbed and converted to heat by the surface coating of the inner absorber, and is transmitted out by the working fluid inside the inner tube of the receiver. The diameters of inner and out tube varies in different system. Considering the spatial distribution in the thermal model for heat transfer performance calculation of solar trough system, it can be divided into zero-dimensional model, one-dimensional model, two-dimensional model and three-dimensional model. For zero-dimensional model,

* Corresponding authors.
E-mail addresses: huangwd@ustc.edu.cn (W. Huang), hupeng@ustc.edu.cn (P. Hu).

http://dx.doi.org/10.1016/j.solener.2016.09.034
0038-092X/

Nomenclature

A	area, m^2
B	interaction coefficient
$B_{eff}(\theta_\perp)$	energy distribution function of reflected ray in radial direction, W/(m^2 rad)
$B_{linear}(\theta_\perp)$	linear brightness distribution function at transverse direction, W/(m^2 rad)
$B_{radial}(\theta)$	radial distribution of solar brightness, W/m^2 sr
C	accommodation coefficient
C_p	constant-pressure specific heat of thermal fluid (J/kg K)
DNI	direct normal incidence, W/m^2
D	mean-free-path between molecules of annular region gas
D	diameter
F	the view factor
f	focus length, m
f_2	the fanning friction factor
f_p	distance from the reflection point to the focus point, m
g	gravitational acceleration (m/s^2)
G	mass flow rate of thermal fluid (kg/s)
h	heat transfer coefficient
I_{in}	incidence solar energy, W/m^2
J	effective radiation
k	thermal conductivity
K	function for calculating the reflectivity, transmittivity, and absorptivity from incident angle
L	length of the parabolic trough reflector, m
n_0	ratio of the refractive index of the glass to that of the refractive index of air
Nu	Nusselt number
n_x	transverse section of the normal vector at the reflection point
P	annulus gas pressure (mmHg)
Pr	Prandtl number
Q	energy
q_{loss}	heat loss of receiver, W/m^2
q_{net}	net energy power in any time, W/m^2
Q_{net}	net energy obtained in a year, J/m^2
r_0	radius of the tube receiver, m
r^*	the ratio of outer to inner diameter of the annular ducts
R	radius of envelope for vacuum tube receiver, m
Ra	Rayleigh number
Re	Reynolds number
t	time, day
T	temperature, K
Tr	transmittivity
w	half width of the parabolic trough reflector, m

Greek symbols

α	absorptivity of vacuum receiver
α'	thermal diffusion coefficient of annulus gas (m^2/s)
γ	ratio of specific heats for the annulus gas, 1.39
δ	molecular diameter of annulus gas, $3.53 \cdot 10^{-8}$ (cm)
$\delta_{latitude}$	local latitude, rad
ε	emissivity
η_0	optical efficiency of parabolic trough solar collector
η_p	optical efficiency at point P
η_t	annual average efficiency
θ	angular displacement in transverse direction, rad
θ_0	maximum angle of ray to the receiver, rad
$\theta_\perp$	angular displacement in transverse direction, rad
$\theta_{\|}$	angular displacement in longitudinal direction, rad
θ'	variable in convolution calculation
λ	incidence angle (rad) or wave length
λ_f	thermal conductivity of thermal fluid (W/m K)
μ	parameter for calculating optical error
ν	kinematic viscosity of annulus gas (m^2/s)
ρ	reflectivity of mirror
σ	Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ (W/m^2 K^4)
σ_{optic}	total optical error, rad
$\sigma_{slopeup}$	standard deviation of the slope errors on upper surface, rad
$\sigma_{slopedown}$	standard deviation of the slope errors on lower surface of the glass, rad
$\sigma_{tracking}$	tracing error, rad
σ_x	standard deviation of the optical error distribution in x direction, rad
σ_{x1}	standard deviation for the refraction of the up surface, rad
σ_{x2}	standard deviation of the ray errors from reflection, rad
σ_{x3}	standard deviation of the ray errors from next refraction, rad
σ_y	standard deviation of the optical error distribution in y direction
τ_g	transmittivity
τ	transmittivity of glass envelope
φ	rim angle of the reflection point, rad
ψ	one coordinate in cylindrical coordinate system, rad

Subscripts and superscripts

a	absorptivity or air
c	conduction
d	annular region
f	fluid
g	glass
i	segment of receiver
in	incidence
inner	inner surface
$linear$	linear distribution
loss	heat loss
m	mean
net	net energy
$radial$	radial distribution
opt	optical
out	out
p	point P
r	radiation
s	side plate of pipe receiver
std	air under standard condition
t	annual average
w	wall of absorber
x	transverse direction
y	longitudinal direction

the relationship between the thermal performance and operating temperature is often obtained by fitting the test results, which can only be applied to the solar collector with the specific receiver although its estimation error is rather small (Lippke, 1995; Patnode, 2006). One-dimensional model usually considers the receiver temperature distribution in radial direction, but ignore the distribution in the axial direction, which can predict system performance with new designs (Dudley et al., 1994; Cheng et al., 2015; Odeh et al., 1998).

In two-dimensional heat transfer model, the temperature distribution of receiver in both radial and axial direction is calculated and the performance of system with new design can be predicted. The