Applied Energy 111 (2013) 581–592

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Heat transfer analysis and numerical simulation of a parabolic trough solar collector

A.A. Hachicha, I. Rodríguez[1], R. Capdevila, A. Oliva*

Centre Tecnològic de Transferència de Calor, Universitat Politècnica de Catalunya, ETSEIAT, Colom 11, 08222 Terrassa, Barcelona, Spain

HIGHLIGHTS

- Heat transfer analysis of the heat collector element is proposed.
- The circumferential distribution of the solar flux around the receiver is studied.
- The sunshape is taken into account in the optical model.
- The overall model is validated with experimental and analytical results.

ARTICLE INFO

Article history:
Received 4 August 2012
Received in revised form 15 February 2013
Accepted 23 April 2013
Available online 10 June 2013

Keywords:
Parabolic trough
CSP
Numerical model
Heat transfer analysis
Optical model

ABSTRACT

Parabolic trough solar collector is the most proven industry-scale solar generation technology today available. The thermal performance of such devices is of major interest for optimising the solar field output and increase the efficiency of power plants. In this paper, a detailed numerical heat transfer model based on the finite volume method for these equipment is presented. In the model, the different elements of the receiver are discretised into several segments in both axial and azimuthal directions and energy balances are applied for each control volume. An optical model is also developed for calculating the non-uniform solar flux distribution around the receiver. This model is based on finite volume method and ray trace techniques and takes into account the finite size of the Sun. The solar heat flux is determined as a pre-processing task and coupled to the energy balance model as a boundary condition for the outer surface of the receiver. The set of algebraic equations are solved simultaneously using direct solvers. The model is thoroughly validated with results from the literature. First, the optical model is compared with known analytical solutions. After that, the performance of the overall model is tested against experimental measurements from Sandia National Laboratories and other un-irradiated receivers experiments. In all cases, results obtained shown a good agreement with experimental and analytical results.

1. Introduction

Concentrated solar power plants are one of the most promising and mature renewable options for electric generation. Parabolic trough collectors (PTC) are the most proven, widespread and commercially tested technology available for solar harnessing. The majority of the parabolic trough plants deployed operate at temperatures up to 400 °C using synthetic oil as heat transfer fluid (HTF) [1].

Many works have been carried out to study the heat transfer process in PTC without taking into account the non-uniformity of the solar radiation and heat losses along the cross-section of the absorber tube. Dudley et al. [2] performed tests at Sandia National Laboratories to determine the thermal losses and thermal efficiency of the PTC used in LS2 Solar Thermal Electric Generation Systems (SEGS). Foristall [3] implemented both a 1D and a two-dimensional model (2D) by dividing the absorber into several segments. A direct steam generation (DSG) collector model was proposed by Odeh et al. [4] based on the absorber wall temperature rather than the working fluid temperature. García-Valladares and Velázquez [5] proposed a numerical simulation of the optical, thermal and fluid dynamic behaviour of a single-pass solar PTC and extended the study by replacing the absorber with a counter-flow concentric circular heat exchangers (double-pass). Stuetzle [6] proposed a 2D unsteady state analysis of solar collector absorber to calculate the collector field outlet temperature: the model was solved by discretising the partial differential equations obtained by the energy balance. Padilla et al. [7] presented a 1D heat transfer

---

* Corresponding author. Tel.: +34 93 739 8192; fax: +34 93 739 8101.

E-mail addresses: ivette@ctc.upc.edu, ivetterp@gmail.com (I. Rodríguez), cttc@cttc.upc.edu (A. Oliva).

URL: http://www.cttc.upc.edu (A. Oliva).

[1] Tel.: +34 937398246; fax: +34 937398020.

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.04.067

Nomenclature

Greek letters

α	absorptance factor
β	thermal expansion coefficient (1/K)
δ	molecular diameter (m)
ϵ	emittance
η	efficiency
γ	intercept factor
κ	absorption coefficient
λ	mean-free path between collisions of a molecule
μ	dynamic viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
ω	ratio of specific heat for the annulus gas
Φ	scattering phase function
ϕ	rim angle
ϕ_s	finite size of the Sun
ρ	density (kg/m^3)
ρ_s	specular reflectance
σ	Stefan–Boltzmann constant 5.67×10^{-8} (W/m^2 K^4)
σ_s	scattering coefficient
τ	transmittance
θ	circumferential direction
φ	angle between the reflected ray and the *x* axis
ξ	thermal diffusivity (m^2/s)

Roman letters

A	area (m^2)
b	interaction coefficient
C_p	specific heat at constant pressure (J/kg K)
D	diameter (m)
e	thickness of the tube (m)
f	focal distance of the parabola
F	view factor
g	gravity (m/s^2)
GC	geometric concentration
h	convective heat transfer coefficient (W/m^2 K)
$\hbar$	enthalpy (J/kg)
H	irradiation (W/m^2)
i	incident direction
I	irradiation per unit length (W/m)
I_b	Planck black body intensity (W/m^2)
J	radiosity (W/m^2)
k	thermal conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
n	normal direction to the reflector surface
N	number of control volumes
Nu	Nusselt number, hD/k
P	pressure (Pa)
Pr	Prandtl number, $\mu C_p/k$
$\dot{q}$	net heat flux per unit of length (W/m)
$\dot{Q}$	power (W)
r	reflected direction
Ra	Rayleigh number, $g\beta\Delta TD^3/(\nu\xi)$
Re	Reynolds number, $\rho vD/\mu$
s	distance travelled by a ray (m)
t	time (s)
T	temperature (K)
v	velocity (m/s)
V	volume (m^3)
W	aperture (m)
$\dot{W}$	work (W)

Subscripts

a	absorber
an	annular region
c	collector
cond	conduction
conv	convection
e	environment
eff	effective
ex	exterior
f	fluid
g	glass envelope
in	input, Inner
inc.	incident
opt	optical
out	output
ref	reflected
s	sky
s.inc.	solar incident
s.rad	solar radiation
std	standard temperature and pressure
t.rad	thermal radiation
th	thermal
u	useful
z	longitudinal direction

model of a PTC taking into account the thermal interaction between adjacent surfaces and neglecting the non-uniformity of the solar flux.

The majority of the published studies about the heat transfer process in the PTC, calculate the heat losses and thermal performance considering the solar radiation as a constant and neglecting the realistic non-uniform solar heat flux in the azimuthal direction. Only a few authors [8] have treated this dependence. Jeter [9,10] presented a mathematical formulation based on the Gaussian function to calculate the concentrated solar flux density and the optical behaviour of a PTC taking into account imperfect reflection, transmission and absorption. Güven and Bannerot [11] established an optical model which used a ray-tracing technique to evaluate the optical performance and determined the optical errors by means of a statistical analysis. He et al. [12] combined the Monte Carlo ray-tracing method (MCRT) with a computational fluid dynamics (CFD) analysis in the HTF to simulate the coupled heat transfer problem.

In the present work, a detailed numerical simulation of the optical and thermal behaviour of a PTC is presented. A new geometrical-numerical method has been developed to simulate the solar heat flux distribution around the absorber tube. The heat collector element (HCE) is discretised into several segments in both axial and azimuthal directions using the Finite Volume Method (FVM) and an energy balance is applied for each control volume. A thermal radiation analysis is carried out between the HCE and the surrounding to calculate the radiative heat losses. The numerical model has been validated with experimental results obtained by Sandia National Laboratories [2] as well as un-irradiated receivers experiments [13] and a good agreement has been obtained. The optical model has been also verified with analytical results of Jeter [9,10] and MCRT results of He et al. [12].

2. PTC numerical model

The general modelling approach is based on an energy balance about the HCE. It includes the direct normal solar irradiation, the optical losses from both, the parabola and the HCE, the thermal losses from the HCE, and the gains in the HTF.