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Sensitivity study of thermal performance characteristics based on optical parameters for direct steam generation in parabolic trough collectors

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ABSTRACT

Solar parabolic trough collector is one of the most potential Concentrated Solar Power (CSP) technologies with high dispatchability. The performance of the Parabolic Trough Collector (PTC) is significantly influenced by the distribution of radiant flux around the line focus receiver. In this paper, an accurate estimation of radiant flux around the line focus receivers of different parabolic trough collectors of varying aperture widths from 5 to 7.5 m has been studied. Effects of total internal reflection in the glass tube, glass tube absorptivity, receiver reflectivity, limb-darkening effect, surface errors and anti-reflective coating have been considered. A direct steam generation model (recirculation mode) has been developed and the effect of geometric errors in the collector on its optical and thermal performance characteristics has been discussed. The thermal efficiency of the direct steam generation collector is influenced by the optical characteristics of the collector and hence the thermal efficiency at different optical errors has been evaluated for the fore-mentioned commercial collectors under the influence of declination. The thermal efficiency is more sensitive to optical errors at low insolation levels and vice versa. For a change in tracking from 0 to 10 mrad, for $PTC_{7.3}$ configuration, thermal efficiency drops by 0.58% at 1000 W/m^2, and 2.02% at 300 W/m^2. The thermal efficiency is also more sensitive to optical errors at higher values of declination. The collector of low geometric concentration ratio has a low sensitivity and low thermal efficiency and vice versa. Hence, the overall efficiency of different collectors at different optical errors has to be studied so as to obtain the appropriate collector configuration for specified optical errors and location of installation. Based on the analysis, graphical results which could aid in the selection of best collectors based on the latitude location, DNI and optical errors has been developed. The evaluation of collectors has also been extended towards power plant characteristics. The nominal power has been set to 50 MW. The location of Jodhpur in India has been selected and the total power generated per unit area has been studied for different collectors, for different optical errors. Based on the graphical results developed, appropriate collectors may be chosen for those locations based on their associated optical errors.

1. Introduction

Concentrating solar power (CSP) technologies, namely parabolic trough collector, dish collector, linear Fresnel reflector and power tower, are capable of producing high temperature steam from solar radiation. Parabolic trough collector (PTC) is a matured CSP system and it can be used for large-scale power generation very effectively with high dispatchability. It concentrates solar radiation two dimensionally on to a line focus receiver which transfers the energy to the working fluid flowing through it. Concentration of solar radiation at the focal region increases the radiant flux intensity over a localized area; increasing the temperature of the working fluid. The efficiency and thermal gradient on the receiver are dependent upon the distribution of radiant flux around it. Hence, the flux distribution analysis around the receiver plays a major role in the performance study of the parabolic trough collector. The flux distribution around the line focus receiver depends on location, structural performance of the system, surface errors causing dispersion and variable distribution of the intensity across the sun known as limb-darkening effect. The flux distribution is also dependent on the total internal reflection in the glass tube, reflectivity of the receiver and absorption of radiation in the glass tube itself. An optical model based on MCRT (Monte-Carlo Ray Tracing) method is developed to study the effect of various mentioned parameters on focal flux distribution.

Direct steam generation in parabolic trough collector is a concept where the water is directly sent through the receiver to be converted to steam. This has a greater advantage compared to the conventional oil based collectors. The overall power plant efficiency could be increased

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Nomenclature

A	area (m^2)
a, b, c	co-ordinates of intersection point of incident radiation on collector surface
d	diameter (m)
DNI	beam radiation at direct normal incidence (W/m^2)
E	total energy over a longitudinal segment (W)
f	focal distance of the parabolic trough collector (m)
h	enthalpy (J/kg)
I_o	maximum intensity at the center of limb darkened sun (W/m^2)
I	intensity at any specific radius in the limb darkened sun (W/m^2)
k	thermal conductivity (W/mK)
L	length (m)
LC_R	local concentration ratio
Ma	molecular mass (kg)
M	transformation matrix
m	mass flux
n	refractive index
nd	day number
n′	normal vector
N	total number of collector loops
p	pressure (N/m^2)
P	power generated per unit collector field area (kWh/m^2)
PG_{net}	nominal power generated by the stand alone solar power plant
PQ	projection of incident ray vector on the XOZ plane
Pr	prandtl number
q	flux intensity (W/m^2)
Q	energy intercepted by the receiver per unit length (W/m)
r′	non-dimensional radius
Re	reynolds number
Bo	boiling number
R	reflected ray vector
RF	refracted ray vector
T	temperature (K)
V	incident ray vector
W	width (m)
x_g	mass fraction
X_{tt}	martinelli parameter
x, y, z	global co-ordinate system
x′, y′, z′	co-ordinate system rotated by tracking error

Greek symbols:

α	heat transfer coefficient ($W/m^2 K$)
β	tracking error (degrees)
γ	angular position on the receiver (degrees)
ε	emissivity
ζ	standard deviation of surface errors
η	efficiency
θ	radial angle made by the incident ray vector with the axis of the cone of rays (degrees)
θ_1	upper limit of radial angle in the concentric disc of a limb darkened sun (degrees)
θ_2	lower limit of radial angle in the concentric disc of a limb darkened sun (degrees)
θ_{max}	maximum radius of the solar disc (degrees)
κ	energy fraction of scattered rays due to total internal reflection
λ	wave-length (m)
μ	dynamic viscosity (Ns/m^2)
ξ	hour angle (degrees)
ρ	reflectivity
ς	angle of refraction through the medium (degrees)
σ	Stephen-Boltzmann constant ($5.67 \times 10^{-8} W/m^2 K^4$)
υ_1, υ_2	random numbers
φ	azimuth angle of the incident ray vector in the cone of rays (degrees)
χ_1, χ_2	empirical constants depending upon the wind speed
ψ	angle between the axis of the cone of rays with its projection on the XOZ plane (degrees)
ω	angle of incidence made by the ray with normal vector of the surface (degrees)

Subscripts:

1, 2	collector row number
a	ambient
ap	aperture
ann	annual
arc	anti-reflective coating
c	collector
cb	convective boiling
c-seg	circumferential segment
cv, rg	convective heat transfer between receiver and glass tube
cv, ga	convective heat transfer from glass tube to ambient
D	dispersion
f	working fluid
g	glass tube
in	inlet
im	incident medium
ir, w	inner receiver wall
l	heat loss
l-seg	longitudinal collector segment
loc	local
max	maximum
Ncb	nucleate boiling coefficient
or, w	outer receiver wall
op	optical
out	outlet
pp	power plant
ref	reflector
red	reduced
rad, rg	radiative heat transfer between receiver and glass tube
rad, ga	radiative heat transfer between glass tube and ambient
recir	recirculation
sr	sunrise
ss	sunset
sat	saturation point
sup	super-heat
th	thermal
u	useful heat gain
vap	vapour
feed	feed water
inj	injection

as the turbine inlet temperature could be increased well beyond 400 °C (oil degrades at this temperature). The thermal efficiency would also increase as the boiling heat transfer coefficient inside the receiver will also be sufficiently high in the DSG collectors. The cost could be reduced as DSG collector eliminates the use of secondary heat exchanger. The DSG collector could be operated in three ways as once-through, recirculation and injection modes. Of these, the recirculation is a well-tested and more reliable mode compared to other methods of