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ScienceDirect

Solar Energy 99 (2014) 134–151

SOLAR ENERGY

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Deflection and stresses in absorber tube of solar parabolic trough due to circumferential and axial flux variations on absorber tube supported at multiple points

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Received 9 July 2013; received in revised form 1 November 2013; accepted 8 November 2013
Available online 5 December 2013

Communicated by: Associate editor Robert Pitz-Paal

Abstract

In a parabolic trough system, the portion of the absorber tube facing the sun receives incident rays directly, whereas the other side receives concentrated rays resulting in circumferential non-uniform flux distribution. Near the sun facing end of the absorber tube, the flux also varies along the length depending upon the rim angle of trough and angle of incidence of sun rays. This circumferential and axial distribution of the solar flux and variation in the fluid temperature result in non-uniform temperature of the absorber tube. The temperature gradient, thus produced, can lead to bending of the tube which may pose the risk of glass cover damage. The absorber tube considered in this work is equidistantly supported at hinges. An analytical expression for deflection in the central axis of the absorber tube (from the focal line of the trough) is derived using circumferential and axial distribution of solar flux incorporating Gaussian sun shape and optical errors. Expressions for radial, circumferential and axial distributions of normal stress and strain induced in the absorber tube are also derived. Effects of angle of incidence of sun rays, optical errors, rim angle of trough, desired rise in fluid temperature and types of supports on deflection and stresses have been studied keeping solar radiation, ambient conditions, fluid, material of absorber tube, receiver's dimensions, aperture width and distance between the consecutive supports fixed. For a desired rise of 0.1 °C/m (averaged over the receiver's length) in the fluid temperature, maximum deflections of −0.57 mm and −1.51 mm have been found out for two types of supports which elevate to −2.71 mm and −7.14 mm respectively when the fluid temperature-rise increases to 1 °C/m (positive and negative signs indicate deflections away and towards the vertex line of the trough respectively). Maximum compressive (negative) stresses increase from 19.29 MPa to 66.61 MPa and tensile (positive) stresses increase from 10.14 MPa to 49.67 MPa as fluid temperature-rise increases from 0.1 °C/m to 1 °C/m. It is found that axial variation in solar flux near the sun facing end of absorber tube plays an important role in deflection.

Keywords: Parabolic trough; Absorber tube; Deflection; Stress

1. Introduction

In a parabolic trough system, the portion of the absorber tube facing the sun receives incident rays directly, whereas the other side receives concentrated rays resulting in circumferential non-uniform flux distribution. The flux also varies significantly in the circumferential direction for the portion that receives concentrated flux only (Jeter, 1986, 1987; Thomas and Guven, 1994; He et al., 2011; Khanna et al., 2013; Cheng et al., 2010, 2012; Wang et al., 2010, 2012). Along the length of the absorber tube, near the sun facing end, the flux varies depending upon the rim angle of the trough and the angle of incidence of sun rays (Khanna et al., 2013). Thus, the flux distribution is non-uniform in circumferential as well as in axial

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http://dx.doi.org/10.1016/j.solener.2013.11.005

Nomenclature

d distance between consecutive supports to absorber tube (m)
E modulus of elasticity of absorber's material (Pa)
f focal length of the trough (m)
h_f convective heat transfer coefficient on inner surface of absorber tube (W/m^2 K)
h_w convective heat transfer coefficient on outer surface of glass cover (W/m^2 K)
I moment of inertia of the cross section of absorber tube with respect to its centroidal axis (m^4)
I_{bn} instantaneous beam normal radiation (W/m^2)
k thermal conductivity of the material of absorber tube (W/m K)
l length of the broken segment of absorber tube after bending (m)
L_c length of the parabolic trough collector (m)
L_t length of the absorber tube (m)
L'_t length of the central axis of absorber tube after elongation (m)
L_1 $(f - r_{to})\tan\psi$
L_2 $(f - r_{to} + w^2/16f)\tan\psi$
L_3 $2(f - r_{to})\tan\psi$
$\dot{m}$ mass flow rate of the fluid (kg/s)
M bending moment (N m)
M_A, M_B moment induced due to the restriction of the rotation of the ends of absorber tube, in $x = 0$ plane (N m)
M_i moment induced in the ith broken segment of absorber tube due to circumferential temperature gradient (N m)
n number of supports to absorber tube
N number of segments in which absorber tube is divided
q_A flux absorbed on the surface of absorber tube per unit outer surface area of absorber tube (W/m^2)
r radius (m)
R reaction (N)
T temperature of absorber tube (K)
T_a ambient temperature (K)
T_f fluid temperature (K)
U_L over all heat loss coefficient (W/m^2 K)
v_w wind velocity (m/s)
w width of the aperture of trough (m)

Greek symbols
α absorptivity of absorber tube
α_{th} thermal expansion coefficient of absorber's material (/K)
δ deflection in central axis of absorber tube from focal line of trough along y axis; positive and negative signs indicate deflections away and towards the vertex line of trough respectively (m)
ΔT_f desired rise in fluid temperature per unit length of absorber tube (averaged over the whole length of absorber tube) (K/m)
Δz length of each broken segment of absorber tube (m)
ε normal strain
ϵ_t emissivity of absorber tube for long wavelength radiation
ϵ_c emissivity of glass cover for long wavelength radiation
θ_{av} angle up to which the circumference of absorber tube receives concentrated rays before considering Gaussian sun shape and optical errors (rad)
θ_{rim} rim angle of the trough (rad)
θ_{un} angle up to which the circumference of absorber tube does not receive concentrated rays before considering Gaussian sun shape and optical errors (rad)
ρ reflectivity of the concentrator surface
ρ_i radius of curvature attained by the central axis of ith broken segment of absorber tube (m)
$\rho\tau\alpha(\psi)$ effective reflectance–transmittance–absorptance product for concentrated rays at ψ angle of incidence of sun rays
σ normal stress; positive sign for tensile stresses and negative for compressive (Pa)
$\sigma_{\mathrm{sun},\psi=0°}$ equivalent rms angular width of sun, at $\psi = 0°$, in line focus geometry (rad)
$\sigma_{optical}$ equivalent rms angular spread caused by all optical errors (rad)
σ_{tot} equivalent rms angular spread caused by optical errors and sun-shape (rad)
τ transmissivity of glass cover
$\tau\alpha(\psi)$ effective transmittance–absorptance product for direct incident rays at ψ angle of incidence of sun rays
ψ angle made by incident sun ray with the normal to aperture plane (rad)

Subscripts
1 supporting arrangement of type 1
2 supporting arrangement of type 2
c glass cover
ci inner surface of glass cover
co outer surface of glass cover
i ith segment of absorber tube and glass cover
$inlet$ inlet of absorber tube
j jth support
t absorber tube
ti inner surface of absorber tube
to outer surface of absorber tube