Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 48 (2014) 123 – 129

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Effect of angle of incidence of sun rays on the bending of absorber tube of solar parabolic trough concentrator

Sourav Khanna*, Suneet Singh, Shireesh B. Kedare

Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

Abstract

In a parabolic trough system, the solar flux distribution on the surface of absorber tube is non-uniform which results in circumferential temperature gradient. Thus, bending moment is induced and leads to the deflection in absorber tube from the focal line of trough. It is concluded that during zero angle of incidence of sun rays (angle made by sun rays with trough's aperture normal), absorber tube will not deflect from the focal line. However, during non-zero angle of incidence, the absorber tube will deflect. It is because of the fact that during non-zero angle of incidence, the absorber tube does not receive any concentrated flux near the end facing the sun. In the current work, an analytical expression is derived for finding the deflection in the central axis of absorber tube from the focal line of trough. Results for deflection are plotted for different values of angle of incidence taking the dimensions of LS3 parabolic trough with Schott 2008 PTR70 receiver.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: Parabolic trough; Absorber tube; Bending

1. Introduction

The flux distribution on the absorber tube is not uniform in circumferential as well as in axial direction [1]. Solar radiation, angle of incidence of sun rays, aperture width and rim angle of trough, optical errors, reflector's reflectivity, dimensions of absorber tube and glass cover, transmissivity of glass cover and refractive index are the

* Corresponding author. Tel.: +919833825295.
E-mail address: sourav.khanna1@gmail.com

1876-6102
Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.015

Nomenclature

E	modulus of elasticity of absorber's material (Pa)
f	focal length of the trough (m)
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 absorber tube and trough (m)
L_1	length upto which the absorber tube will not receive any concentrated flux (m)
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_T	moment induced in the absorber tube due to circumferential temperature gradient (N-m)
r	radius (m)
R	reaction (N)
T	temperature of absorber tube (K)
T_a	ambient temperature (K)
T_f	fluid temperature (K)
w	width of the aperture of trough (m)

Subscripts

ci	inner surface of glass cover
co	outer surface of glass cover
inlet	inlet of absorber tube
ti	inner surface of absorber tube
to	outer surface of absorber tube

Greek Symbols

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)
θ_{rim}	rim angle of the trough (rad)
ψ	angle made by incident sun ray with the normal to aperture plane (rad)

parameters affecting the flux distribution on the absorber tube. Khanna et al. [1] have derived an expression for finding the distribution of flux incorporating the effect of Gaussian sun shape and optical errors.

Such flux distribution results in a non-uniform radial, circumferential and axial distribution of the temperature of absorber tube [2]. Absorptivity and emissivity of absorber tube, emissivity of glass cover, ambient temperature, wind velocity, material properties of absorber tube, properties of gas filled in the annulus space between absorber tube and glass cover, thermal properties of fluid and desired rise in fluid temperature (or mass flow rate) are the parameters affecting the temperature distribution of absorber tube in addition to the parameters that affect flux distribution. Khanna et al. [2] have derived an explicit expression for radial, circumferential and axial distribution of absorber's temperature.

Non-uniform temperature distribution leads to differential expansion of the absorber tube resulting in compression and tension in its different parts. It can lead to bending of the tube and the glass cover, used for reducing heat losses and maintaining evacuation, can be broken [1]. Extent of bending depends on the properties of material of absorber tube and the types of supports used to support the absorber tube in addition to the parameters that affect temperature distribution [3]. Yaghoubi and Akbari [4] have considered the absorber tube to be supported at its ends. Absorber tube is free to expand axially and free to bend. Deflection in the central axis of absorber tube from the focal line of trough is calculated using ANSYS software. Using CFD software, Wang et al. [5] have computed the thermal stresses induced in the absorber tube if it is not allowed to expand axially and to bend. Wang et al. [6] have extended their previous work to compare different materials of absorber in terms of induced thermal stresses. It is observed that the effect of axial variation in flux near the sun facing end of absorber tube (supported only at its ends) on deflection in absorber tube is not reported in literature.

2. Methodology

The parabolic trough collector having aperture width (w), rim angle (θ_{rim}) and length (L) has been considered for this study. An absorber tube with a concentric glass cover is attached to the trough such that its central axis is aligned with the focal line of trough. Fig. 1 shows the cross sectional view of the system. The geometry of the trough is defined by Cartesian coordinates (x, y, z) and that of absorber tube and glass cover by cylindrical coordinates (r, θ, z). The extreme point (O) of the sun facing end of vertex line of trough is taken as origin of the cartesian coordinate system. The extreme point (O') of the sun facing end of central axis of absorber tube is taken as origin of the cylindrical coordinate system. The angle θ is named as circumferential angle of the absorber tube and is measured from OO' in anti-clockwise direction (Fig. 1). The inner and outer radii of absorber tube and glass cover are r_{ti}, r_{to}, r_{ci} and r_{co} respectively.

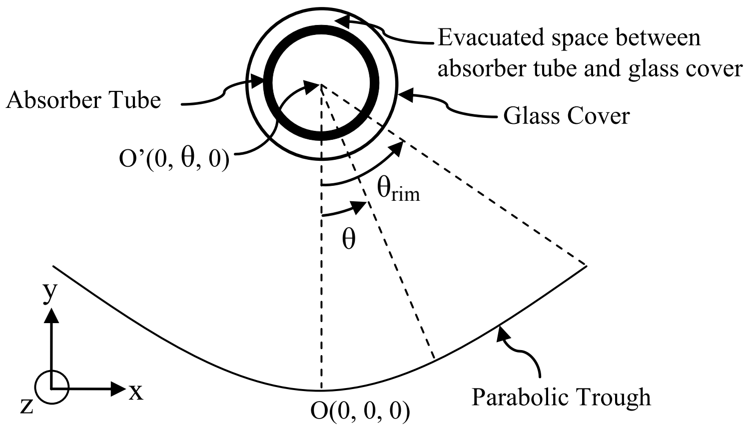

Fig. 1. Shading and blocking of one row due to other [3]

The non-uniform circumferential distribution of solar flux on the surface of absorber tube results in circumferntial temperature gradient [2]. It will induce a moment (M_T) in the absorber tube which may leads to deflection in absorber tube from the focal line of trough. The moment induced in the absorber tube due to its weight is not considered in this wok. The expression for M_T can be given as [3]

$$M_T = E\alpha_{th} \int_{-\pi}^{\pi} \int_{r_{ti}}^{r_{to}} T(r,\theta) r^2 \cos\theta \, dr \, d\theta \tag{1}$$

The absorber's temperature distribution, $T(r,\theta)$, is symmetric in x-y plane about θ=0° or y axis due to the symmetry of trough-receiver system [2]. Thus, the deflection in the central axis of absorber tube from the focal line of trough, $\delta(z)$, occurs only in x = 0 plane (the plane passing through the vertex line and focal line of trough) [3].

Moment induced due to the weigth In other words, *δ(z)* gives the measure of the deflection in any cross section of absorber tube at length z from its original position along y axis. Its sign is negative if cross section deflects towards the vertex line of trough and positive if deflection is in the opposite direction to the vertex line.

The segment of absorber tube lying between z = 0m and $z = L_1$, does not receive any concentrated flux during non-zero angle of incidence of sun rays. L_1 can be estimated as [1]

$$L_1 = (f - r_{to})\tan\psi \tag{2}$$

This axial non-uniformity in solar flux and the supporting arrangement of absorber tube will play an important role in deflections. The supporting arrangement of absorber tube is shown in Fig. 2. Supports can move axially facilitating the absorber tube to elongate freely. The free-body diagram of the absorber tube is shown in Fig. 3.

In Fig. 3, R_1 and R_2 are the reactions at the supporting points. M_A and M_B are the moments that are induced due to the restriction of rotation of absorber tube at its ends in x = 0 plane.

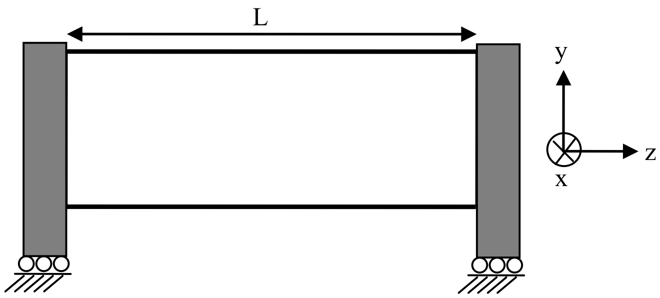

Fig. 2. View of the supporting arrangement of absorber tube as seen along x axis

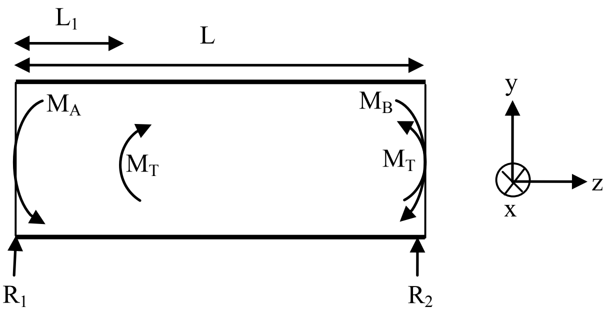

Fig. 3. Free-body diagram

Absorber tube is not allowed to deflect along y axis at the points where it is supported. Thus, *δ(z)* is zero at those points and can be written as

$$\delta(z) = 0 \quad \text{for } z = 0 \text{ and L} \tag{3}$$

Since absorber tube is not allowed to rotate at its ends in x = 0 plane, slopes of deflected absorber tube will be zero at those points and can be written as

$$\frac{d\{\delta(z)\}}{dz} = 0 \quad \text{for } z = 0 \text{ and L} \tag{4}$$

Equilibrium of reactions and moments (Fig. 3) give the following equalities

$$R_1 + R_2 = 0 \tag{5}$$

$$R_1 L - M_A + M_B = 0 \tag{6}$$

Taking moment equilibrium at each point z and using singularity function [7], the expression for bending moment can be written as

$$M(z) = R_1 z - M_A + M_T[(z - L_1)^+]^0 \tag{7}$$

'+' sign on the bracket means only positive values have to be taken. If the quantity inside the bracket is less than or equal to zero, 0 will be taken. Beer et al. [7] have given the following relation between $\delta(z)$ and $M(z)$

$$\frac{d^2\{\delta(z)\}}{dz^2} = \frac{M(z)}{EI} \tag{8}$$

Solving Eq. (8) the following expression of $\delta(z)$is derived

$$\delta(z) = \frac{R_1 z^3}{6EI} - \frac{M_A z^2}{2EI} + \frac{M_T[(z - L_1)^+]^2}{2EI} + C_1 z + C_2 \tag{9}$$

R_1, R_2, M_A, M_B, C_1 and C_2 can be found out using Eqs. (3-6).

3. Results and discussion

In the current work, calculations have been carried out using the dimensions of Schott 2008 PTR70 receiver and LS-3 parabolic trough collector (Table 1). Therminol VP1 is chosen as heat transfer fluid. Mass flow rate of fluid is chosen so as to meet the requirement of desired rise in fluid temperature ΔT_f = 0.6°C/m (averaged over the whole length of tube).

Table 1. Values of the parameters chosen for producing the results

Parameters	Values	Parameters	Values	Parameters	Values	Parameters	Values
r_{co}	0.06m	w	5.76m	E	190GPa	ΔT_f	0.6°C/m
r_{ci}	0.057m	θ_{rim}	80°	k	Function of	T_a	30°C
r_{to}	0.035m	L	4m		temperature [17]	I_{bn}	950W/m^2
r_{ti}	0.033m	α_{th}	17.3 x10^{-6}/°C	$T_{f,\ inlet}$	293°C	ψ	20°

Using the temperature distribution of absorber tube [2] and Eq. (1), M_T is found to be 311N-m. For ψ = 0°, 20° and 40°, values of L_1 (Eq. 2) are 0m, 0.61m, 1.41m respectively. The corresponding values of deflections are plotted in Fig. 4. Results show that absorber tube will not deflect from the focal line at ψ = 0°. However, it will deflect during non-zero angle of incidence due to the fact that the sun facing end of absorber tube does not receive any concentrated rays.

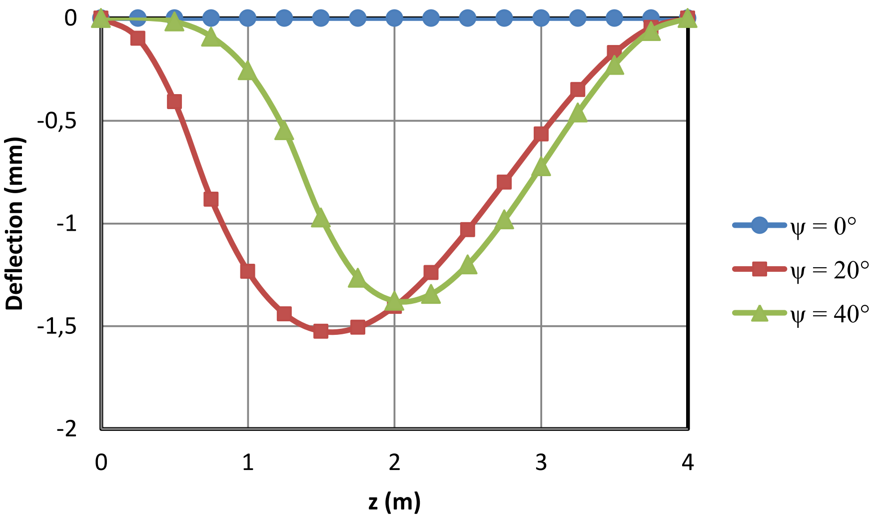

Fig. 4. Variation in deflection in absorber tube for various values of angle of incidence of sun rays (ψ)

Using the absorber's temperature distributions [2] at ΔT_f = 0.2, 0.6 and 1°C/m, the calculated values of M_T (Eq. 1) are 143, 311 and 427 N-m respectively. The corresponding values of deflections are plotted in Fig. 5. Results show that as ΔT_f increases deflection increases. It is due to the fact that as ΔT_f increases, circumferential temperature gradient increases [2] and M_T increases.

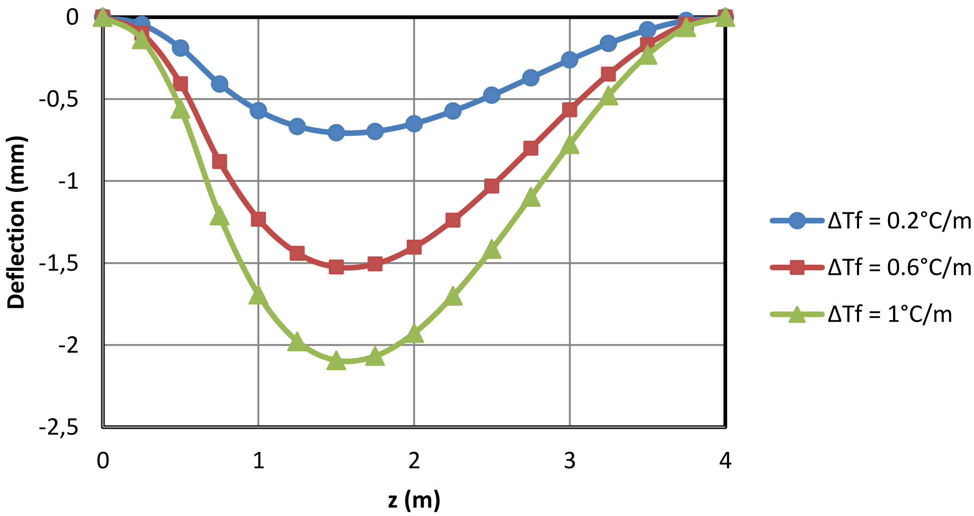

Fig. 5. Variation in deflection in absorber tube for various values of desired rise in fluid temperature (ΔT_f)

4. Conclusions

In the present work, an analytical expression for deflection in the central axis of absorber tube (from the focal line of trough) has been derived. During non-zero angle of incidence of sun rays, the sun facing end of absorber tube does not receive any concentrated flux. It is concluded that this axial variation in flux (near the sun facing end) results in the deflection of absorber tube.

References

[1] Khanna S, Kedare SB, Singh S. Analytical expression for circumferential and axial distribution of absorbed flux on a bent absorber tube of solar parabolic trough concentrator. Solar Energy 2013;92:26-40.
[2] Khanna S., Singh S, Kedare SB. Explicit expression for radial, circumferential and axial distribution of temperature of absorber tube of solar parabolic trough concentrator. (yet to be published)
[3] Khanna S., Singh S, Kedare SB. Deflection and stresses in absorber tube of solar parabolic trough due to circumferential and axial flux variations on absorber tube supported at n number of points. (yet to be published)
[4] Yaghoubi M, Akbari MM. Three dimensional thermal expansion analysis of an absorber tube in a parabolic trough collector. SolarPACES 2011.
[5] Wang F, Shuai Y, Yuan Y, Yang G, Tan H. Thermal stress analysis of eccentric tube receiver using concentrated solar radiation. Solar Energy 2010;84:1809-15.
[6] Wang F, Shuai Y, Yuan Y, Liu B. Effects of material selection on the thermal stresses of tube receiver under concentrated solar irradiation. Materials and Design 2012;33:284-291.
[7] Beer FP, Johnston ER, Dewolf JT, Mazurek DF. Mechanics of materials. 5th ed. New Delhi: The Tata McGraw Hill Education Private Limited; 2010.