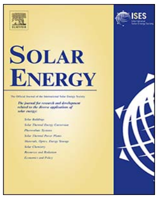
Solar Energy 163 (2018) 471–485

Contents lists available at ScienceDirect

Solar Energy

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



Structural analysis of absorber tube used in parabolic trough solar collector and effect of materials on its bending: A computational study

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ARTICLE INFO

Keywords:
Solar thermal
Parabolic trough
Bimetallic
Tetra-layered laminate
Stress
Deflection

ABSTRACT

The maximum deflection of a Parabolic Trough Solar Collector (PTSC) absorber tube is a result of the circumferential non-uniformity in temperature distribution and self-weight. This non-uniformity in temperature is a factor of incoming solar flux distribution as well as material property of the absorber tube. The present work focuses on structural analysis of absorber tube used in PTSC and the effects of variations of material. Multiphysics platform, namely thermal-fluid analysis and structural analysis has been made in this regard. The computational investigation has been carried out on Schott PTR70 2008 receiver and Therminol VP1 as the Heat Transfer Fluid (HTF). Evacuated annular space along with specular and non-grey nature of glass cover which is semi-transparent to the input flux has been modeled to obtain better accuracy in results. The materials investigated are steel, copper, aluminum and various laminated composites like bimetallic (Cu-Fe) and tetra-layered laminate (Cu-Al-SiC-Fe), which are subjected to different mass flow rate of HTF at the absorber tube inlet with constant heat flux on the absorber tube outer surface. It is found that the change in the material of the absorber tube has a negligible effect on the amount of heat transferred to the HTF, but it has a significant effect on the bending due to thermal expansion as well as due to self-weight. Steel absorber tube is generally used, but its lower thermal conductivity results in poor circumferential temperature distributions. Copper has better thermal characteristics, but higher self-weight and lower mechanical strength compared to steel. So a combined effect of these properties is utilized in bimetallic tube, which results in a decrease in maximum deflection by 7–15% as compared to steel. As the self-weight of the absorber tube plays a vital role in deflection, therefore a tetra-layered laminate absorber tube having lower weight and improved temperature distribution results in a decrease in maximum deflection by 45–49% as compared to steel.

1. Introduction

Parabolic Trough Solar Collector (PTSC) is one of the most proven technologies among the various concentrating type solar collectors for electricity generation and production of steam for Industrial Process Heating (IPH). PTSC consists of a metallic absorber tube which is coaxial with the focal line of the parabolic reflector. Absorber tube receives concentrated solar rays reflected from a parabolic trough. A Heat Transfer Fluid (HTF) flows within the absorber tube, to which heat is transferred from the heated tube wall. PTSC receiver has a glass covering over the absorber tube and the annulus region between the absorber tube and glass cover is evacuated (vacuum) to minimize the heat loss due to convection and radiation. Usually, a selective coating is provided on the absorber tube. The selective coating typically has an absorptance value of 0.94–0.95 and a very low value of emittance (0.07–0.1) in order to reduce radiation heat loss (Goswami, 2015).

The circumferential non-uniformity of the temperature distribution observed on the surface of the absorber tube is a combination of different factors, like the characteristics of the flux distribution on the absorber tube surface and material properties of the absorber tube material. The flux distribution on the absorber tube surface depends upon the factors like rim angle of the reflector, the shadow of the absorber tube on the parabolic reflector, efficiency of reflection of the parabolic reflector, its solidity factor and the local intercept factor (Khanna et al., 2013). The above factors coupled with the fact that upper half of the absorber tube receives non-concentrated rays and lower half receives concentrated rays, gives rise to a characteristic flux distribution which has been presented by Cheng et al. (2010) using Monte Carlo Ray Tracing (MCRT) method. Cheng et al. (2010) numerically computed the temperature distribution of the absorber tube surface, circumferential and longitudinal temperature variation using FLUENT.

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https://doi.org/10.1016/j.solener.2018.02.028
Received 14 September 2017; Received in revised form 7 February 2018; Accepted 9 February 2018

Nomenclature

b	width of the aperture of trough (m)
D_g	glass diameter (mm)
d	diameter (mm)
E	modulus of elasticity of absorber tube material (GPa)
f	focal length of the trough (m)
h	convective heat transfer coefficient (W/m^2 K)
I_{bn}	incident beam radiation (W/m^2)
k	thermal conductivity of absorber tube (W/m-K)
L	length (m)
L_t	length of absorber tube (m)
$\dot{m}$	mass flow rate (kg/s)
Re	Reynolds number
r	radius (mm)
r_t	radius of absorber tube (mm)
t	thickness (mm)
T	temperature (K)
T_a	ambient temperature (K)
ΔT_f	HTF temperature change per unit length (K/m)
ΔT_c	circumferential temperature difference (K)
T_{in}	HTF inlet temperature (K)
T_{out}	HTF outlet temperature (K)
v_w	wind velocity (m/s)
W	weight of absorber tube per unit length (N/m)
Z	axial distance (mm)

Abbreviations

CFD	computational fluid dynamics
DO	discrete ordinates
HTF	heat transfer fluid
MCRT	monte carlo ray trace
PTSC	parabolic trough solar collector
SIMPLEC	semi-implicit method for pressure linked equations-consistent

Greek symbols

α	absorptivity of absorber tube
α_{th}	thermal expansion coefficient of absorber's material (/K)
β_t	tracing angle of trough (degree)
δ	deflection (mm)
δ_{max}	maximum deflection (mm)
ε	turbulent kinetic energy dissipation rate (m^2 s^3)
ϵ_c	emissivity of glass cover
ϵ_t	emissivity of absorber tube
ρ_c	reflectivity of concentrator surface
ρ	density (kg/m^3)
τ	transmissivity of glass cover
θ_{rim}	rim angle (degree)
θ	incidence angle (degree) or polar angle
θ_{shd}	shadow region angle (degree)
σ	stress (MPa)
κ_{in}	turbulent intensity
κ	turbulence kinetic energy (m^2 s^2)
ν	Poisson's ratio

Subscripts

a	axial
c	circumferential
ci	inner surface of glass cover
co	outer surface of glass cover
eff	effective
f	fluid
i	inner
o	outer
r	radial
t	absorber tube
ti	inner surface of steel tube
to	outer surface of steel tube

Khanna et al. (2013) obtained an analytical expression for the absorbed flux on a bent absorber tube considering circumferential and axial variations in temperature of the absorber tube. They concluded that the bending reduces heat flux incident on the absorber tube. The increase in circumferential non-uniformity in temperature will result in increased deflection and stresses. Khanna et al. (2015) have found out the amount of deflection of the PTSC absorber tube due to the effect of fluid temperature rise from inlet to outlet (ΔT_f= 0.1–0.5 °C/m) using an analytical technique. They have observed that deflection increases with increase in fluid temperature rise (ΔT_f). They also observed a decrease in absorber tube deflection when provision is made for support at multiple points along the absorber tube length. Khanna et al. (2016a) have carried out an experimental investigation of the deflection of the absorber tube supported at multiple points. Khanna et al. (2016b) have further extended their previous work by proposing an analytical expression for temperature distribution on a bimetallic absorber tube. Use of bimetallic absorber tube reduces the circumferential temperature gradient (ΔT_c) as compared to the steel absorber tube. The appropriate thicknesses and materials of inner and outer layers of the bimetallic tube have also been studied.

Sahoo et al. (2010) have carried out numerical investigations on the parabolic trough absorber tube without considering glass cover on the absorber tube. Parameters like wind speed, mass flow rate of the fluid, variations in incident solar flux and use of various materials as absorber tube were analyzed. The less circumferential temperature difference in case of copper absorber tube as compared to steel tube was observed. Wang et al. (2010) have used an eccentric absorber tube with optimum eccentricity and 90° oriented angle with an aim to reduce the thermal stresses of the receiver. They observed a reduction of Von-Mises stress up to 41.1% and substantial reduction in thermal stress when the orientation angle is between 0° and 90°. Wang et al. (2012) observed that the steel absorber tube has the highest stress failure ratio, while copper tube has the lowest. This is due to the fact that copper has higher thermal conductivity and uniform circumferential temperature distribution when compared to the steel absorber tube.

Abedini-Sanigy et al. (2015) have numerically studied the thermal gradients as well as thermal stresses developed in the absorber tube for four specific days namely, Spring Equinox, Summer Solstice, Autumnal Equinox and Winter Solstice. They found out that by increasing the inlet temperature of HTF the circumferential temperature difference decreases. They also found out deflection is more during Summer Solstice than other days. Akbarimoosavi and Yaghoubi (2014) have determined the thermal stress and strain for two separate PTSC systems. They determined the appropriate flow rate and convective heat transfer coefficient for each season in order to reduce the bending of the receiver tube. The Higher convection coefficient is required in Spring than Autumn, as higher incident heat flux in spring causes higher ΔT_c. They also suggested the use of higher thermally conductive material for the absorber tube to reduce ΔT_c.

Almanza et al. (1997) have studied the behavior of PTSC under direct steam generation (DSG) system. By replacing the steel absorber tube with copper tube, the ΔT_c reduces, which results in a decrease in the thermal stress in the wall of the absorber tube. Flores and Almanza (2004) have stated that the most significant deformation of an absorber