Solar Energy 174 (2018) 912–922

Contents lists available at ScienceDirect

Solar Energy

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

Numerical model of solar external receiver tubes: Influence of mechanical boundary conditions and temperature variation in thermoelastic stresses

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ARTICLE INFO

Keywords:
Solar external receiver
Thermal stress
Temperature gradients
Thin-walled cylinder

ABSTRACT

Failure in solar external receivers is mainly originated from the thermal stress, caused by the high non-uniform transient solar flux. The heat-up and cooldown of tube receivers in daily cycles produce low-cycle fatigue that limits the lifetime of tubes. The corrosion of tube materials produced by incompatibility between the decomposed heat transfer fluid and tube material may increase this issue.

The temperature spatial distribution in these tubes has strong variations in radial, circumferential, and axial directions. The stress field, produced by the temperature gradients, has been commonly analyzed using bidimensional models in isolated tube cross sections, without taking into account the axial temperature variation, the mechanical boundary conditions, and the temperature-dependent thermomechanical properties.

In this work, a three-dimensional finite element model has been developed in order to calculate the stress field distribution, without performing any geometrical simplification. In addition, appropriate mechanical boundary conditions have been imposed in order to adequately simulate the tube behavior. Besides, radial, circumferential and axial temperature variations have been studied separately to analyze how each of them influences the maximum stress distribution. This 3D model has been compared with analytical solutions for the two-dimensional thermal stress problem in circular hollow cylinders.

The results show that the boundary conditions have a significant effect on the tube stresses, increasing the axial stress component and therefore the equivalent stress.

The analysis of each of the temperature variations showed that the circumferential variation temperature is the one that produces most of the stress, since it tries to strongly bend the tube, which is impeded by the boundary conditions.

The results also present that 2D models are not capable of obtaining the correct stress distribution along the tube, since they are not taking into account the longitudinal supports. By contrast, the maximum stress can be obtained with confidence using the analytical stress solution of the angular and radial temperature variation around a hollow circular cylinder.

1. Introduction

Molten salt external receivers are tubular heat exchangers subjected to complex thermo-mechanical loads. The cyclic and non-homogeneous heat flux distribution is responsible for temperature gradients and thermal stresses, and the boundary conditions of the tubes caused by the supports increase these stresses. The most important role of solar central receivers is to keep the intercept solar flux within the tube mechanical safety limits.

Thermal stresses are produced when a temperature variation of the material occurs in presence of constraints (Barron and Barron, 2011). Solids present internal constraints that originate thermal stresses; they appear because strong temperature gradients produce different dilatation displacements for vicinity material points.

Thermal stresses could be produced also by external constraints, like supports. These constraints prevent some displacements of the system in presence of temperature gradients. Reaction forces appear in the supports to prevent the displacement of the system, which must be limited to avoid shades and contact between tubes, since it may cause overcooling and overheating respectively.

Nowadays, the direct measurement of the incident solar flux distribution, the tube wall temperature and the stress profiles is impracticable during the receiver operation. An inaccurate estimation of the tube wall temperature and the stresses can damage the tubes,

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https://doi.org/10.1016/j.solener.2018.09.068
Received 19 March 2018; Received in revised form 20 September 2018; Accepted 24 September 2018

Nomenclature

Roman symbols

A	tube cross section area (m^2)
a	tube inner radius (m)
B, D	Fourier coefficients
b	tube outer radius (m)
E	Young's modulus [Pa]
K	geometric thermal stress term [K]
r	tolar radial coordinate [m]
T	temperature [K]
$\overline{T}$	mean temperature [K]
ΔT	temperature difference between inner and outer surfaces of cylinder [K]
z	coordinate in the axial direction [m]

Greek symbols

α	linear thermal expansion coefficient [K^{-1}]
ε	deformation
Δ	difference operator
ν	Poisson's ratio
Θ	polar angular coordinate [rad]
σ	stress [MPa]

Abbreviations

HTF	heat transfer fluid

Subscripts

i	inner surface
o	outer surface
Θ	circumferential component
r	radial component
z	axial component
VM	Von Mises

risking the whole power plant operation. Therefore, the development of thermo-mechanical models to predict the temperature and the stresses in the tubes of the receiver is of great interest.

Numerous are the thermal and mechanical models that can be found in the literature to analyze solar receivers. However, most of them are only focus in the thermoelastic behavior of these systems, forgetting the mechanical restrictions: Kent and Ark (1931) analyzed thermal stress in thin-walled cylinders, with temperature variation in radial and axial directions, however, not in the circumferential one. Goodier (1937, 1957), studied the thermal stress in thin-walled cylinders whose thickness and temperature distribution may vary around the circumference. Sauer (1996) developed formulae for the analysis of axial stress in pipes due to thermal stratification, but with no radial temperature variation. Wagner (2008) developed a complete model to analyze the receiver's behavior, however, he considered no circumferential variation on the wall temperature of the tubes. Du et al. (2016) developed a model to analyze the thermal stresses and the fatigue in molten salt receivers using basic thermal elasticity equations and they compared it with numerical simulations; they considered circumferential variation of the incident solar flux, but they did not take into account the mechanical restrictions of the tubes. Neises et al. (2014) developed an approach to calculate the thermal and pressure stresses on the receivers, without considering mechanical constraints. Marugán-Cruz et al. (2016) carried out a numerical study of the stresses in thin-walled pipes subjected to a non-uniform heat flux using Gatewood (1941) formulation. They highlighted the importance of the Reynolds, Prandtl and Biot numbers in the problem; however, they did not consider the external constraints. Irfan and Chapman (2009) characterized the thermal stresses in radiant tubes due to axial, circumferential and radial temperature gradients; although these tubes were not part of a solar receiver, they showed very interesting results, even if they assumed no mechanical restrictions in the tubes. Recently, Logie et al. (2018) calculated the 2D thermoelastic stress in concentrating solar receiver tubes employing classical thermoelasticity equations.

There are other studies related to stress in solar receivers that are not focused on the tube characterization. For example, Wang et al. (2012) studied how to select the most adequate material in the receiver as a function of the thermal stresses; they pointed that stainless steel has a high failure ratio, however it is the most typical material in the receivers. Uhlig et al. (2017) considered the mechanical restrictions of the receiver, focusing their analysis on the stresses that occur in the panel headers due to the ovens heating.

This study is focused on the characterization of the thermal stresses produced by the two types of constraints, internal and external, in molten salt solar receivers. The stress origin will be studied in order to understand how these constraints affect to the stress distribution. Besides, the importance of internal and external constraints has been studied separately considering or not the supports along the tubes.

This work is organized as follows: in the following section the receiver geometry and constrains have been defined. In Section 3 the models used to characterize the thermal and mechanical behavior of the receiver have been described. In Section 4 the methodology developed by Logie et al. (2018) to calculate thermal stress is introduced. Section 5 shows the results obtained with the numerical model, for different boundary conditions. Besides, numerical and analytical results are compared in Section 5. Finally, the main conclusions of this study are presented in Section 6.

2. Studied geometry

To calculate the thermal stresses in a receiver tube, a solar power tower with molten salt as heat transfer fluid, similar to Gemasolar, has been analyzed.

Gemasolar solar plant is located in Fuentes de Andalucía, Spain, at 37.56° north latitude. Its solar field is radial staggered layout slightly biased to the north, with the highest radius equal to 850 m. Gemasolar field consists of 2650 square heliostats of 10.95 m side, which are distributed in three different zones: the inner one has a radial cornfield configuration and the two external zones are staggered. The position of each heliostat has been determined with scaled aerial images of the solar plant. The reflectivity, the cleanliness and the tracking errors of the mirrors have been obtained from Sánchez-González et al. (2017).

Gemasolar receiver tower is 120 m high. The solar receiver is a cylindrical absorber with 10 m height and an aspect ratio 1.17. The circular perimeter is composed of 18 vertical panels of 1.5 meters width, integrated each of them by 60 tubes of 2.24 cm external diameter and 1.2 mm thickness. Stainless steel with high nickel content is the preferable material in solar receivers; since no information of the tube material has been obtained, alloy 800H has been selected as the tube material. To increase the tubes absorptivity, they are coated on the outside face with black Pyromark.

The receiver tubes intercept the solar radiation reflected by the heliostats and transmit it to the heat transfer fluid (HTF) that flows inside them. In Gemasolar, the HTF is solar salt (60% $NaNO_3$ - 40% KNO_3) that enters in the receiver at 290 °C and exits at 565 °C. The mass flow rate of molten salt in the receiver depends on the incident solar