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Effects of material selection on the thermal stresses of tube receiver under concentrated solar irradiation

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ABSTRACT

Material selection of tube receiver is a critical issue to ensure the reliability during its whole service life. In this study, the thermal stress analyses of tube receiver under concentrated solar irradiation condition using various materials are carried out. The concentrated solar irradiation heat flux distribution is obtained by Monte-Carlo ray tracing method and used as boundary conditions of the Computational Fluid Dynamics (CFD) analysis. The CFD analysis will solve the temperature fields and the resulted temperature fields defined at the nodes of CFD analysis meshes are interpolated as input data to the nodes of the thermal stress analysis meshes. The temperature fields, thermal stress fields of various material conditions are obtained in the numerical analysis. The numerical results show that the temperature gradients and effective stresses of the stainless steel and silicon carbide (SiC) conditions are significantly higher than that of the aluminum and copper conditions. The stress failure ratio is introduced to assess the thermal stress level of each material condition. The stainless steel condition has the highest stress failure ratio and the copper condition has the lowest stress failure ratio. From the standpoint of thermal stress, copper is recommended to be the material of tube receiver.

1. Introduction

The parabolic trough concentrator with tube receiver is one of the most suitable systems for solar power generation. The parabolic trough concentrator concentrates the incoming solar irradiation on the periphery of the tube receiver. The tube receiver converts the concentrated solar irradiation into heat which transfers heat to the circulating fluid through convection. As designed to operate with concentrated heat fluxes, the tube receiver will be subjected to the high thermal stresses which may cause the failure of glass envelope and receivers [1]. For example: in the Solar Power Plant of the National University of Mexico (SPNUM), the stainless steel tube receiver with parabolic troughs have occurred frequently deflection and glass envelope rupture during experimental test and application [2–4]. Greater understanding of the temperature distributions and thermal stress fields of tube receiver using various materials by numerical methods can give very useful instructions for application [5].

Numerous studies have been carried out to investigate the temperature distributions and thermal stress fields of tubes and receivers with various material conditions. A numerical analysis had been conducted by Chen and Liu [6] to study the effect of using porous material for the receiver on temperature distributions. Experiments were conducted by Fend [7] to research the temperature distributions on the volumetric receivers used two novel porous materials. A finite element analysis was conducted by Islamoglu [8] to study the temperature distribution and the thermal stress fields on the tube heat exchanger using the SiC material. To reduce the thermal stresses, Agrafiotis et al. [9] employed porous monolithic multi-channeled SiC honeycombs as the material for an open volumetric receiver. Low cycle fatigue test of the receiver materials was conducted at different temperatures by Lata et al. [10], the results showed that the high nickel alloys had excellent thermo-mechanical properties compared to the austenitic stainless steel. Almanza and Flores [4] have proposed a bimetallic Cu–Fe type receiver, and the experimental test results showed that, when operated at low pressure, the bimetallic Cu–Fe type receiver had a lower thermal gradient and less thermal stress strain than the steel receiver. In the SPNUM, the stainless steel tube receiver for parabolic trough concentrator deflected as a wave during the experimental tests to examine the receiver behavior. When a copper tube receiver was used instead of a steel one, no appreciable bending of the pipe was observed during application [3].

The literature survey shows that few research papers have been published on the thermal stress field's analysis of tube receiver under concentrated solar irradiation condition using various materials. In this study, four different materials (stainless steel, aluminum, copper, SiC) are employed for the numerical analysis. The

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Nomenclature

A_i	the area of *i*th surface (m^2)
A_p	the area of concentrator (m^2)
A_r	the area of receiver (m^2)
C_r	concentration ratio
d_{in}	inner diameter of receiver (m)
d_{out}	outer diameter of receiver (m)
E	modulus of elasticity (GPa)
$E_{\text{sun},\Delta\lambda_k}$	sun average spectral irradiance at the spectral band $\Delta\lambda_k$
F_c	failure coefficient (%)
L	length of tube receiver (m)
M_b	total spectral bands
N_i	total bundles
n_s	number of bundle samplings
q_b	heat flux on bottom surface (W/m^2)
$q_{r,j}$	concentrated heat flux (W/m^2)
q_s	solar irradiation heat flux (W/m^2)
q_t	heat flux on top surface (W/m^2)
r	radius (m)
r_i	inner radius of tube receiver
r_o	outer radius of tube receiver
R_r	random number
RD_{ij}	radiative exchange factor
T_f	fluid temperature (K)
T_{in}	fluid inlet temperature (K)

Greek Symbols

α	thermal expansion coefficient
θ	angle (degree)
μ	fluid velocity (m/s)
μ_{in}	inlet fluid velocity (m/s)
v	Poisson's ratio
σ_{eff}	effective stress (MPa)
σ_r	radial stress (MPa)
σ_z	axial stress (MPa)
σ_θ	tangential stress (MPa)
$\Delta\lambda_k$	spectral band

concentrated solar irradiation heat flux distribution is obtained by Monte-Carlo ray tracing method and is used as boundary conditions for the steady state heat transfer analysis. The heat transfer analysis will solve the temperature distributions and the resulted temperature distributions defined at the nodes of the CFD meshes are interpolated as input data to the nodes in the thermal stress analysis meshes. The temperature gradients, thermal stress fields and stress failure ratios of different material conditions are obtained and compared to give suggestions on material selection.

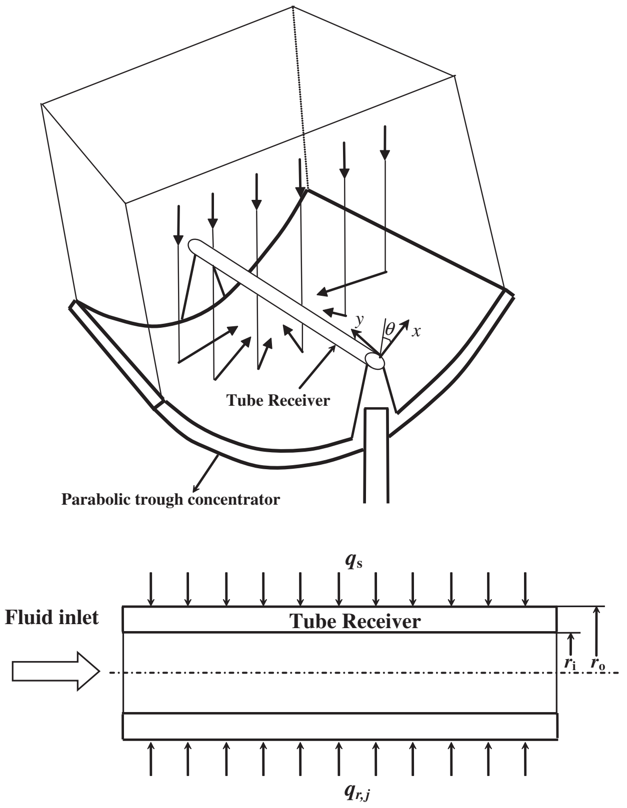

Fig. 1. Schematics of the tube receiver with solar parabolic trough system.

2. Methodology

A thermal model proposed for the tube receiver with solar parabolic trough concentrator system is shown in Fig. 1. As seen from this figure, the incoming solar irradiation is concentrated on the bottom surface of the tube receiver by the parabolic trough concentrator. Due to the highly concentrated solar irradiation, the tube receiver may be subjected to considerable degree of thermal stress.

2.1. The calculation of heat flux distribution

A Monte-Carlo ray tracing computational code, which is based on the radiative exchange factor (REF) theory, is developed to predict the heat flux distribution on the bottom periphery of the tube receiver. The REF RD_{ij} is defined as the fraction of the emissive power absorbed by the *j*th element in the overall power emitted by the *i*th element. The *j*th element can absorb the emissive power within the system by means of direct radiation, direct reflection and multiple reflections. The values of the RD_{ij} are determined by both the geometrical and radiative characteristics of the computational elements.The REF within the spectral band $\Delta\lambda_k$ ($k = 1, 2, ..., M_b$) can be expressed as follows:

$$RD_{i,j,\Delta\lambda_k} = N_{i,j}/N_i \tag{1}$$

where N_i is the total bundles emitted by the *i*th element, $N_{i,j}$ is the bundles absorbed by the *j*th element, and M_b is the total spectral bands of the wavelength-dependent radiation characteristics of the surface. As shown in Fig. 1, the concentrated heat flux distribution on the bottom surface of the tube receiver can be expressed as follows:

$$q_{r,j} = \frac{A_i}{A_j}\sum_{k=1}^{M_b} RD_{i,j,\Delta\lambda_k} E_{sun,\Delta\lambda_k} \tag{2}$$

where $q_{r,j}$ is the heat flux of the *j*th surface element of the tube receiver, A_i is the area of the imaginary emission surface, A_j is the area of the *j*th surface element of the tube receiver, and $E_{sun,\Delta\lambda_k}$ is the sun average spectral irradiance within the spectral band $\Delta\lambda_k$. More information about the Monte-Carlo ray tracing method can be found in Ref. [11].

The geometrical parameters of the parabolic trough concentrator and the tube receiver for this study are chosen from Ref. [12] and the parameters are illustrated in Table 1. In order to increase the absorption of solar radiation and minimize radiation heat loss,