Applied Thermal Engineering 99 (2016) 741–750

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Analysis of thermal stress and fatigue fracture for the solar tower molten salt receiver

Bao-Cun Du, Ya-Ling He *, Zhang-Jing Zheng, Ze-Dong Cheng

Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

HIGHLIGHTS

- A solar tower molten salt receiver tube with non-uniform heat flux is numerically investigated.
- The thermal stress is calculated theoretically by solving thermal stress equations.
- The minimum heat flux formula is derived when damage occurs on the tube wall.
- Allowable critical crack total length on outer wall is analyzed using CTOD method.

ARTICLE INFO

Article history:
Received 7 August 2015
Accepted 10 January 2016
Available online 1 February 2016

Keywords:
Solar energy utilization
Tower molten salt receiver
Thermal stress
Fatigue fracture
Minimum heat flux

ABSTRACT

In this paper, the thermal stress and fatigue fracture of a single tube for the solar tower molten salt receiver are presented. First, the temperature distribution of the tube is simulated. Second, the thermal stress is calculated by solving stress equations. Then the minimum heat flux formula is derived when damage occurs on wall based on the yield criterion and heat conduction equation. Finally, the critical crack length on outer wall is investigated by using the Crack Tip Opening Displacement (CTOD) method. The results show that the distribution of stress is similar to that of inner/outer wall temperature difference. The maximum stress, which causes plastic deformation, occurs on outer wall. According to the minimum heat flux formula $q \geq [\sigma_s]/\left(K\sqrt{A^2+B^2+C^2-AB-AC-BC}\right)$ derived in this paper, the heat flux is only 0.19 MW·m^{-2} when damage appears on the receiver tube if the inlet temperature and safety factor are 560 K and 1.5 respectively. Furthermore, the critical crack length is 17 mm when the heat flux is 0.7 MW·m^{-2}.

1. Introduction

The solar tower plant has been developed rapidly and many demonstration plants have been built all over the world up to now [1–3]. However, higher cost and lower efficiency are always the challenging problem in the tower plant. During these years, it has been found that the tower plant could operate at lower cost and higher efficiency when the molten salt is used as heat transfer and storage medium [4–7]. And the medium of molten salt has been used in the MSEE [8,9] and Solar Two [10] tower plants, the THEMIS [11] and Solar Tres [12] tower plants. The solar tower molten salt power technology has become one of the main trends in the solar power field.

The molten salt receiver often needs to undergo non-uniform irradiation of a peak heat flux up to 1.0 MW·m^{-2}, and the higher heat flux would lead to greater temperature gradient between inner and outer tube walls [13], which would easily cause thermal stress. Then the plastic deformation could happen on the wall if the thermal stress is higher than the yield strength [14]. Furthermore, the thermal stress or strain would change repeatedly due to frequent startup and shutdown of receiver during day and night, which will lead to fatigue fracture at the higher stress/strain locations. For example, the defect of thermal fatigue cracks and even fracture have appeared in the boiler components such as the steam manifold and water-wall tube in operation [15–18].

There are five stages [19,20] when fatigue fracture occurs in material, including deformation, damage accumulation, crack initiation, crack stable growth and unstable propagation to fracture, as shown in Fig. 1. For a single receiver tube, the cyclic thermal stress leads to cycle slip strain on the tube wall. The linear elastic deformation would occur even when the thermal stress is lower than the yield strength, and then the fatigue damage happens on wall. If the damage is accumulated to a certain degree, the crack initiates at the location of local defects (inclusions, holes, dislocations, etc.) on the tube wall. Then, the crack stably grows under the action of cyclic thermal stress, and the direction between crack and tensile stress is perpendicular to each other. Finally, the phenomenon of crack unstable propagation to fracture happens if the crack length

* Corresponding author. Tel.: +86 029 82665930; fax: +86 029 82665445.
E-mail address: yalinghe@mail.xjtu.edu.cn (Y.-L. He).

http://dx.doi.org/10.1016/j.applthermaleng.2016.01.101
1359-4311/

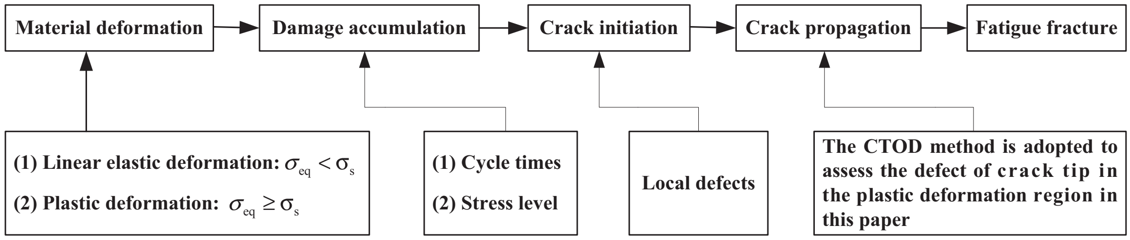

Fig. 1. The destruction behavior of material.

a exceeds the critical length a_c [21]. Therefore, the crack length a on the wall should be lower than the critical length a_c to avoid fatigue fracture in the receiver tube. In addition, plastic deformation in short times would not induce the tube fracture immediately, but causes the accumulation of plastic damages. After a certain heat cycle of plastic deformation, the crack occurs on the wall surface. The fatigue fracture may happen especially when the tube experiences repeated plastic deformation caused by the cycle thermal stress. However, the process of causing damage on the tube wall is difficult to analyze quantitatively under the action of low cyclic stress, which is lower than the yield stress. It is argued that the yield criterion can be adopted to judge whether the damage happens on the receiver tube because the stress is constant when the plastic deformation occurs.

At present, besides the solar flux density distribution simulation on the tower receiver [22–25], most of the researches of the receiver are mainly focused on the complex flow and heat transfer characteristics [26–33]. Especially for the molten salt tube, some scholars have used numerical and experimental methods to investigate the steady-state heat transfer characteristics of molten salt in a single receiver tube. For example, Wu et al. [34] analyzed the convection heat transfer performance of a molten salt receiver tube in the laminar-turbulent transition region, then the heat transfer correlation of transition flow was obtained. Yang et al. [35] experimentally investigated the relationship between the heat transfer characteristic and the thermal efficiency of the receiver tube. In Ref. [36], the heat transfer characteristic also has been simulated numerically by applying non-uniform heat flux in the circumferential direction on the tube, and the temperature distribution of the tube was then obtained. In addition, the thermal performance of molten salt receiver was also studied experimentally in Ref. [37].

However, few papers have focused on the thermal stress and fatigue fracture in the molten salt receiver up to now. In this paper, a three-dimensional model of a single tube is established, and the boundary condition of non-uniform heat flux is applied on the outer side wall using user-defined functions (UDF) method, thus the wall temperature can be simulated numerically. Based on the results of temperature, the thermal stress is calculated by solving the thermal stress equations. Furthermore, the minimum heat flux formula is derived when damage occurs on the wall according to the yield criterion and the tube wall heat conduction equation. Finally, the critical crack length on the outer wall is investigated by using the Crack Tip Opening Displacement (CTOD) method of elasticity and plasticity.

2. Model and method

2.1. Physical model

The material of the receiver tube is 316H stainless steel, and the inner/outer radius and length are 10.5/12.5 mm and 3 m respectively. The properties [38–41] for this material are listed in Table 1; the yield strength with different temperatures are shown in Fig. 2, and the linear thermal expansion coefficient and elastic modulus functions [39] are shown in Eqs. (1) and (2).

$$\alpha = 1.43\times10^{-5} + 7.34\times10^{-9}T - 2.65\times10^{-12}T^2 \quad (1)$$

$$E = 2.11\times10^{11} - 3.59\times10^{7}T - 3.75\times10^{4}T^2 \quad (2)$$

In addition, the binary molten salt that consists of 40%wt KNO_3 and 60%wt $NaNO_3$ is used as the heat transfer fluid in this paper. The melting point and decomposition temperature are 480 K and 873 K respectively. The properties [42] of the binary molten salt can be seen in Eqs. (3) and (6).

$$\rho = 2263.94 - 0.64T \quad (3)$$

$$c_p = 1395.87 + 0.17T \quad (4)$$

$$\lambda = 0.39 + 0.19\times10^{-3}T \quad (5)$$

$$\mu = 9.85\times10^{-4} + 0.72e^{-T/99.3} \quad (6)$$

2.2. Governing equations and boundary conditions

The governing equations of heat transfer in the molten salt receiver tube consist of continuity equation, momentum equation,

Table 1
Properties of 316H stainless steel.

Parameters	λ	ρ	c_p	v	σ_b
Units	$W{\cdot}m^{-1}{\cdot}K^{-1}$	$kg{\cdot}m^{-3}$	$J{\cdot}kg^{-1}{\cdot}K^{-1}$	–	MPa
Values	21.5	7090	500	0.3	515

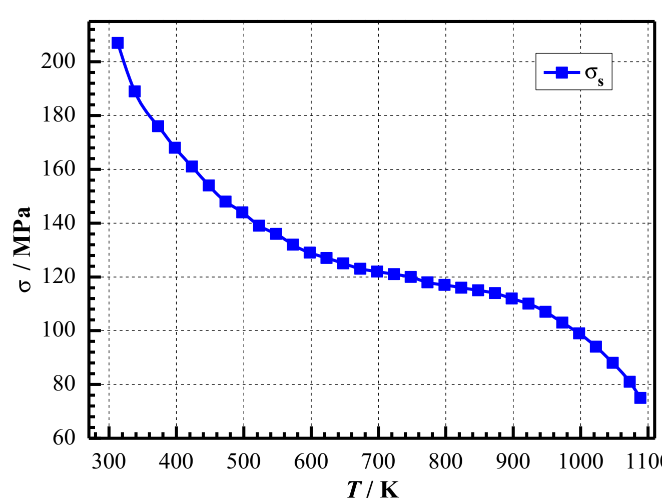

Fig. 2. Yield strength of 316H stainless steel.