Thermal performance and stress analyses of the cavity receiver tube in the parabolic trough solar collector

F Cao, Y Li, L Wang and T Y Zhu

College of Mechanical and Electrical Engineering, Hohai University, Changzhou, China

E-mail: fcao@hhu.edu.cn

Abstract. A light ray tracing model and a heat transfer model were built to analyse the heat flux distribution and heat transfer in a 1m cavity receiver tube with Parabolic Trough Collectors as the concentrator. The numerical methods were used to simulate the thermal stress and deformation of the receiver tube. The temperature fields of the receiver tube and the thermal stress distribution in the steel tube at the cross section and along the fluid flowing direction were presented. It is obtained from this study that non-uniform heat flux distribution is absorbed at the receiver tube outer surface due to the structure of the cavity receiver tube. Temperature fields in the steel receiver tube at the inlet and the outlet match well with the incident solar radiation. An eccentric circle temperature gradient is observed at cross section of the outlet fluid. The equivalent stress is a complex result of solar heating flux, energy transfer inside the PTC and the fluid and steel characteristics. Highest deformation is 3.1mm at 0.82m. On increasing the fluid mass flow rate, higher fluid mass flow rate results in higher equivalent stress along the absorber tube.

1. Introduction

Solar energy has been recognized as one of the most important energy sources at present and in the further energy consumption. Due to the discontinuous, low energy flux, periodicity and unsteady characteristics of solar energy, solar concentration is commonly utilized in solar engineering fields, among which the solar parabolic trough collectors (PTC) are the earliest and most widely accepted solar concentration style [1]. There have been many studies on the PTC, which can be generally classified as: the light ray tracing analysis under different structural [2-6], the collector tube thermal performance analysis [7-9], the thermal stress analysis [10-15] and the system performance evaluation [16-18].

Solar energy is reflected by the parabolic trough reflector, which generate nonlinear solar radiation distribution. There are also several types of solar receivers, such as the flat plate [2], the tube [3,14,15] and the cavity [19-21]. Solar radiation on the receiver is simulated through tracing each solar light [2-4] and the structural is also optimized according to the solar radiation distribution [5-6]. Serrano-Aguilera et al. proposed an Inverse Monte Carlo Ray Tracing method to calculate the numerical description of the PTC. Their method is expected to define continuous linear reflectors for flat plat receivers, where a quasi-planar concentrated flux distribution is required [2]. Cheng et al. made a three-dimensional...
numerical study of heat transfer characteristics in the receiver tube of PTC [3]. Based on the methodology, they then carried out a comparative analysis for PTC with a detailed Monte Carlo ray-tracing optical model [4]. They concluded that the ideal comprehensive characteristics and optical performance of the PTC systems were very different from some critical points determined by the divergence phenomenon of the non-parallel solar beam [4]. Liang et al. compared three optical models for the PTC, and optimized the geometric parameters according to their models [5]. Cheng et al. optimized the geometrical structure of the PTC based on the particle swarm optimization algorithm and the Monte Carlo ray-tracing method, which found a balance between the calculating speed and result accuracy [6]. As solar heating flux reaches the absorber, it will heat the fluid inside the absorber [7-9]. Kumar and Reddy carried out a 3-D numerical analysis of the porous disc line receiver for PTCs and investigated the influences of thermic fluid properties, receiver design and solar radiation concentration on overall heat collection [7]. Liang et al. summarized and compared the one-dimensional mathematical models under different assumptions and details for PTCs in the literature [8]. Huang et al. proposed a new analytical model for optical performance and a modified integration algorithm, with which the structural, operation and sun tracking parameters can be changed conveniently [9]. The solar heating flux and the temperature and pressure inside the absorbers can be utilized to analyze the thermal stress of the PTCs [10-15]. Giannuzzi et al. defined a guideline for steel structures design and assessment of components of PTC. The codes were developed for practical usage and were evaluated under some specific conditions [10]. Du et al. analyzed thermal stress and fatigue fracture of a single tube for the solar tower molten salt receiver and concluded that the distribution of stress was similar to that of inner/outer wall temperature difference [11]. Henshall et al. focused on the analysis of evacuated enclosures for flat-plate solar collectors and concluded that with a suitably low temperature sealing process vacuum the designed enclosure can successfully withstand imposed stresses [12]. Wu et al. derived the distribution of temperature field and stress field of a typical PTC and found that the maximum equivalent stress on the collector had close relationship with the convective heat transfer coefficient inside the collector [13]. Cui et al. studied thermal stress of DSG solar absorber tube in stratified two-phase regime and argued that the heat transfer difference of vapor and liquid phases are of high importance on analyzing the effective stress and deflection [14]. Wang et al. studied the effects of material selection on the thermal stresses of tube receiver and concluded that the stainless steel condition has the highest stress failure ratio and the copper condition has the lowest stress failure ratio [15]. As the thermal stress is analyzed and the strength of the receivers is satisfied, the PTC is coupled into the thermodynamic cycles to generate steam or power [16-18]. Zadeh et al. introduced the genetic algorithm and sequential quadratic programming into the thermal optimization of the PTC and analyzed the influences of the operation parameters like the nanoparticle concentration ratio and the operation temperature [16]. Kumaresan et al. reported an experimental study on performance of a PTC integrated with a storage unit and analyzed the parameters like the collector's useful heat gain and thermal efficiencies [17]. Reddy et al. carried out energetic and exergetic analyses for the components of the solar PTC power system and obtained the influences of the operation pressure and load conditions to the energetic and exergetic efficiencies [18].

Some special structural are also utilized for the PV or PV/T in PTC [3]. However, tube receivers are more commonly used in PTC circulation combined with Rankine Cycle [16-18]. In general, two kinds of tubes are utilized in the PTC, viz. the vacuum tube [2, 4-13] and the cavity tube [19-21]. Main advantages of the vacuum tube are the high thermal maintenances and low module cost, whereas the structural is fragile. Though a kind of metal inner and vacuum glass outer tube is proposed, the connection area of metal and glass is also fragile due to uninterrupted and periodical thermal stress from the inner and outer sides. The other kind of solar receiver is the cavity tube, whose schematic is shown in Figure 1. The outer cover of the receiver is elliptic, with an open inlet towards the parabolic trough reflector. The incoming solar lights are reflected by the parabolic trough reflector and entered into the absorber through the open inlet. Solar lights are then reflected for several times and finally reached the receiver tube at the ellipse focus. There are some studies on the thermal performance of the solar cavity receivers [19-21]. Very limited studies have been presented to analyze the thermal
stress on the solar tube inside the ellipse cavity. Considering this, the thermal performance of the cavity receiver in the parabolic trough solar collectors is first analyzed. Then, the thermal stress of the receiver tube is presented through numerical simulation using STAR-CCM+ and Abaqus.

![Figure 1. Schematic of the cavity receiver tube in the parabolic trough solar collecting system.](image)

2. Mathematical model

2.1. Solar ray tracing

To track the solar ray transferring in the PTC, a coordinate system is built as shown in Figure 2. The major and minor axes and the focal distance of the elliptic are $2a$, $2b$ and $2c$ respectively. The focal distance and open length of the parabola are $f$ and $B$ respectively. According to the coordinate system, the elliptic cavity and the parabolic reflector can be expressed as:

$$
\frac{(x - f - c)^2}{a^2} + \frac{y^2}{b^2} = 1
$$

(1)

$$
y^2 = 4fx
$$

(2)

![Figure 2. Sun light trance in the parabolic trough solar cavity collector](image)
The marginal light BG can be expressed as:

\[ y = -k_1(x - c) \]  

(3)

where:

\[ k_1 = \frac{-B}{B^2 - 2f} \]  

(4)

\[ \beta = \arctan k_1 \]  

(5)

The other marginal light is AC, which is reflected by the cavity inner surface and generates the
tangent line of the absorber tube \( l_4 \). The slope for \( l_4 \) is

\[ k_4 = \frac{k_2 - k_1 + k_3(1 + k_2k_3)}{1 + k_2k_3 - (k_2 - k_3)k_3} \]  

(6)

where

\[ k_3 = \frac{-b^2(m-f-c)}{a^2n} \]  

(7)

Correspondingly, in order to reach the absorber tube inside the cavity, the relationship between the
absorber tube radius and the light slopes is:

\[ \frac{|k_4(f + 2c) - k_5m + n|}{\sqrt{k_4^2 + 1}} \leq r_{tube} \]  

(8)

2.2. Thermal balance in the cavity

The schematic of the thermal balance in the cavity is shown in Figure 3. The energy balance of the
tube steel wall is:

\[ Q_{38\text{SolAbs}} = Q_{23\text{cond}} + Q_{35\text{rad}} + Q_{36\text{rad}} + Q_{34\text{conv}} \]  

(9)

where \( Q_{38\text{SolAbs}} \) is the solar radiation absorbed by the receiver tube, \( Q_{23\text{cond}} \) is the heat conduction
through the steel wall, \( Q_{35\text{rad}} \) is the radiation exchange between the steel tube and the gall at the cavity
inlet, \( Q_{36\text{rad}} \) is the radiation exchange between the cavity inner surface and the steel tube, \( Q_{34\text{conv}} \) is the
heat convection between the steel tube and the fluid inside it.
The energy balance of the cavity glass is:

$$Q_7 \text{SolAbs} + Q_{45} \text{conv} + Q_{56} \text{cond} + Q_{57} \text{cond} + Q_{7,10} \text{rad} = Q_{7,10} \text{conv} + Q_{7,10} \text{rad}$$

(10)

where $Q_7 \text{SolAbs}$ is the heat absorbed by the cavity glass, $Q_{56} \text{cond}$ is the heat conduction between the cavity inner surface and the glass, $Q_{45} \text{conv}$ is the heat convection between the glass and the air inside the cavity, $Q_{7,10} \text{rad}$ is the radiation exchange between the glass and the atmosphere and $Q_{57} \text{cond}$ is the heat conduction between the two surfaces of the glass.

The energy balance of the air inside the cavity is:

$$Q_4 \text{SolAbs} + Q_{43} \text{conv} = Q_{45} \text{conv}$$

(11)

2.3. Solutions

Equation (1)-(8) are then converted into the codes to calculate the radiation distribution on the steel absorber tube. After obtaining the solar radiation absorbed by the receiver tube, $Q_3 \text{SolAbs}$, the thermal balance inside the cavity is then calculated according to Equation (9)-(11). After that, the thermal stress of the receiver tube is presented using STAR-CCM+ and Abaqus.

3. Results and discussion

3.1. Thermal flux on the absorber tube

Dimensions of the cavity receiver tube are summarized in Table 1. Distributions of the light and heat flux around the receiver tube outer surface are shown in Figure 4 (a) and (b) respectively. It is found from the figure that the sun light is sheltered by the cavity, which causes no light and heat flux from 0° to 10° at Figure 4. (a). The other light enters the cavity and reaches the absorber tube, leading to the first increase of the heat flux from 10° to 30°. A minor peak appears at 26° because of the circular receiving surface. After that, the direct light from the cavity open inlet and the reflected light from the elliptic inner surface are merged from 40° to 90°, generating a peak at 56°. The reflected sun light from the elliptic inner surface then enters the absorber surface from 90° to 125°. No light can reach the range between 125° and 180°.
Table 1. Parameters of the cavity and absorber tube

| Parameter/Unit         | Value   |
|------------------------|---------|
| Concentration ratio    | 16.6    |
| Major axis/mm          | 50      |
| Minor axis/mm          | 30      |
| PTC focal distance /mm | 800     |
| Elliptic focal distance/mm | 40   |
| PTC open width /mm     | 1000    |
| Absorber tube radius /mm | 18    |
| Absorber tube length /m | 1.0    |

3.2. Temperature distribution in the absorber tube

The temperature distributions in the absorber tube at the inlet and the outlet under fluid mass flow rate of 0.1 kg/s are shown in Figure 5. The temperature and pressure of the inlet fluid are 270 °C and 5MPa respectively. It is found from the figure that the highest temperature of the steel receiver tube increases from 284.86 °C at the inlet to 287.07 °C at the outlet. Temperature fields in the steel receiver tube at the inlet and the outlet are similar, which matches well with the incident solar radiation, following the principle that higher solar radiation generates higher steel receiver wall temperature. Kumar and Reddy also found the similar tendency of the radiation distribution and the wall temperature [7]. The fluid inside the receiver tube, however, differs a lot from the inlet to the outlet. The fluid inlet temperature is uniform at the inlet, which is settled by the boundary conditions. As the fluid is heated along the receiver tube, its temperature reaches 280 °C at the outlet. And its temperature distribution is not uniform, with higher fluid temperature at the steel wall with higher temperature. And an eccentric circle temperature gradient is observed in Figure 5 (b).

![Figure 4. Distributions of the light and heat flux around the receiver tube outer surface.](image-url)
3.3. Thermal stress in the absorber tube

After obtaining the temperature distributions at the steel tube receiver, the equivalent stresses and the deformation of the receiver tube can be simulated using STAR-CCM+ and Abaqus. The equivalent stress along the fluid direction, along the radial direction and at the tube outer surface and the deformation of the tube along the fluid direction are shown in Figure 6.

It is found from Figure 6 that the equivalent stress along the radial direction nearly remains at 16 MPa at the heating side and 7.1 MPa at the non-heating side. The equivalent stress at the cross section of the receiver tube decreases from 0° to 47°, then increases from 47° to 85°, then decreases till 142° and finally increases till 180°. The peak equivalent stress locates at 0°, with the value of 16.4 MPa. The equivalent stress in the wall of the cross section increases linearly. The deformation along the axis increases from the inlet, with the peak of 3.1mm at 0.82m. Then the deformation has a fluctuation, with a valley of 2.4mm at 0.89m.

The equivalent stress is a complex result of solar heating flux, energy transfer inside the PTC and the fluid and steel characteristics. First of all, the solar radiation heats the steel tube and is transferred into the tube through the steel wall, which generates the temperature difference between the inner and outer wall. Du et al. demonstrated the similar tendency between the thermal stress and the inner/outer wall temperature difference [11]. Then, the heating flux is transferred into the fluid inside the tube through heat convection, which generates the temperature difference between the inner wall and the fluid. Even though the fluid is in liquid or vapor phase, it still has effects on the steel walls. Wu et al. had concluded the close relationship between the thermal stress and the convective heat transfer coefficient inside the collector [13]. Finally, as fluid is continuously heated inside the tube, phase change will occur under suitable conditions, which leads to different thermal stresses onto the tube inner wall. Cui et al. argued that the heat transfer difference of vapor and liquid phases are of high importance on analyzing the effective stress and deflection [14]. In general, the thermal stress is generated by the temperature difference between the tube inner/outer wall and the fluid inside the tube, the fluid pressure and the fluid state.
Figure 6. Equivalent stress along the fluid direction, along the radial direction and at the tube outer surface and the deformation of the tube along the fluid direction.

Figure 7. Equivalent stress at the outlet under different fluid mass flow rates.

3.4. Thermal stress under different water mass flow rates

As the inside fluid property affects the equivalent stress and deformation of the steel receiver tube, different fluid mass flow rates are considered in Figure 7. It is found that the equivalent stress distributions in the absorber tube along the fluid direction have the similar tendencies under different fluid mass flow rates, following the rule that higher fluid mass flow rate leading to higher equivalent stress.

4. Conclusions

Solar parabolic trough collectors (PTC) are the most widely accepted solar concentration style. The PTC with cavity receiver tube has not been well discussed in the literature. In the present study, a ray
tracing model and a heat transfer model were built to analyze the heat flux distribution and heat transfer in a 1m cavity receiver tube. The temperature fields of the receiver tube and the thermal stress distributions of the steel tube at the cross section and along the fluid flowing direction were obtained. The following conclusions are obtained through this study:

- A non-uniform heat flux distribution is absorbed at the receiver tube outer surface due to the structure of the cavity receiver tube.
- Temperature fields in the steel receiver tube at the inlet and the outlet match well with the incident solar heat flux. An eccentric circle temperature gradient is observed at cross section of the outlet fluid.
- The thermal stress is generated by the temperature difference between the tube inner/outer wall and the fluid inside the tube, the fluid pressure and the fluid phase, which are caused by solar heating flux, energy transfer inside the PTC and the fluid and steel characteristics. The highest deformation in this study is 3.1mm at 0.82m.
- On increasing the fluid mass flow rate, higher fluid mass flow rate results in higher equivalent stress along the absorber tube.

Acknowledgement
This research was funded by the National Natural Science Foundation of China (No.: 51506043) and the Fundamental Research Funds for the Central Universities (No.: 2014B19714).

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