Numerical simulation of the temperature distribution of elliptical cavity tube receivers in the parabolic trough solar collector

Fei Cao*, Xianzhe Gu, Jialing Qiu, Chunyuan Yang and Tianyu Zhu

College of Mechanical and Electrical Engineering, Hohai University, China

For correspondence: Dr. Fei Cao, fcao@hhu.edu.cn

Abstract. The elliptic cavity tube absorber is used in the parabolic trough solar collectors to increase the optical efficiency and decrease the thermal loss. But the non-uniform heat flux distribution on the tube receiver will cause non-uniform temperature distribution, thus leading to asymmetric thermal stress and deformation of the tube receiver. In this paper, the geometric as well as thermal parameters of the elliptical cavity tube receiver are analysed through numerical simulation. The temperature distribution of the tube receiver in the single-phase liquid zone, viz. the water zone and the vapour zone, is analysed. It is found from this study that there are two extreme temperature areas in the elliptical cavity tube receiver. When the major semi-axis of the elliptical cavity is 63 mm, the maximum temperature of the water zone is the largest, which occurs at (-35 mm, 0 mm) of the tube receiver. When the major semi-axis of the elliptical cavity is 67 mm, the maximum temperature appears at (-9 mm, 0 mm) in the vapour zone, and the minimum temperature rise appears at (-13.88 mm, 0 mm).

1. Introduction

With the development of economy and the growth of population, the global demand for energy continues to increase. The use of fossil energy will not only bring the problem of the environmental pollution, but also face the problem of resource exhaustion. Improving and adjusting the energy structure and utilization of renewable clean energy has become the common strategy of all countries in the world. Solar energy is one of the most promising sources of renewable energy. Due to the low energy flux, discontinuousness and unsteady characteristics of solar energy, solar concentrators are usually utilized to generate high temperature for thermochemistry, power generation purposes [1]. The parabolic trough solar concentrator holds high concentration ratio and marketization. But the high temperature on the outer wall of the absorber tube also generates high energy loss to the environment. To solve this problem, the elliptic cavity tube absorber is proposed. Boyd proposed a kind of cylindrical cavity, whose section was a cylinder with an opening. The outer layer of the cylinder was covered with a layer of insulation to reduce heat loss, and the working medium was heated in the tank [2]. Barra improved its structure by adding a V-shaped mirror at the opening of the cavity and uniformly arranging 8 circular tubes in the cylinder. The 8 circular tubes were heated by the air in the cavity [3]. Considering that part of the sunlight of Barra’s cavity-type collector cannot reach the tube receiver, Yu et al. connected the tube cluster and the inner wall of the cavity together, and used the cavity as the fin to enhance heat transfer [4]. Cao et al. proposed a new type of elliptical cavity collector tube based on the blackbody technology [5]. The elliptical cavity was mainly composed of three parts: the tube absorber, the insulation layer and the glass cavity. Studies also show that the heat
flux distribution on the tube receiver is not uniform, which will lead to non-uniform temperature distribution on the absorber tube. Asymmetric thermal stress will occur under the non-uniform temperature distribution and leads to non-uniform thermal deformation of the tube receiver. The tube receiver will deviate from the parabolic focal line, thus the optical and the thermal efficiency will both decrease [6]. Wang et al. analysed the thermal stress of the tube receiver at non-uniform heat flux through ANSYS [7]. The results showed that the residual stress at the joint of the glass and the absorption tube was the main reason of the failure of the vacuum collector tube. Pacheco et al. analysed the variation of thermal stress in the tube receiver under the condition of thermal shock. The closer the tube absorber is to the inner wall, the greater the thermal stress will be. The stress first increased with time, and then decreased with time as the wall gradually stabilizes [8]. Almanza et al. conducted a study on the deformation of the heat absorber tubes in the DSG parabolic trough solar collector in the layered flow region, and the results showed that the temperature gradient of the tube absorber was the main reason for the bending deformation of the steel tubes [9]. Later, they analysed the heat transfer characteristics of the tube absorber. The analysis results showed that when the cold water entered the tube absorber, due to the large circumferential temperature difference of the tube absorber, it would be bent and deformed [10]. Verlotski et al. analysed the thermal stress of the tube absorber. Influences of the material and the working fluid on the stress of the heat absorber were carried out. Their study showed that the material of the heat absorber should be selected according to the thermal stress and thermal fatigue of the tube absorber, and the thermal stress could be reduced by controlling the flow rate of the fluid inside the tube absorber [11]. Mohammad et al. simulated and discussed free convection heat transfer of a suspension of Nano–Encapsulated Phase Change Materials (NEPCMs) in an inclined porous cavity [13]. Based on the referred studies, the elliptic cavity absorber is analysed in the present study. The heat flux distribution, temperature distribution is numerically simulated by considering different elliptic cavity geometries and working fluid.

2. Geometry of the elliptical cavity collector
The geometry of an elliptical cavity collector is shown in Fig. 1. It is composed of three parts: a parabolic trough solar collector, an elliptical cavity and a tube receiver. The incident solar irradiation is reflected by the parabolic trough solar collector and enters the elliptical cavity through the open channel. The concentrated solar radiation then reflected several times on the inner wall of the elliptical and finally reaches the tube receiver, which locates at one focus point of the elliptical cavity.

![Fig. 1 Geometry of the elliptical cavity collector.](image)

In order to obtain the solar radiation distribution on the tube receiver, a coordinate system is set up as shown in Fig. 2. The length of the metal heat absorption tube, L is 1m, and the diameter of the outer wall and inner wall of the heat absorption tube, viz. \(D_1\) and \(D_2\) in Fig. 2, are 70mm and 66mm respectively. As shown in Fig. 2, the position of the tube receiver near the elliptical open channel is 0°. The direction of the tube receiver away from the elliptical cavity open channel is 180°, and the angle rotates clockwise. With the centre of the heat absorption tube being the origin, the direction parallel to the heat flux is the X-axis. In order to reduce the influence of flow pattern on heat transfer, a 0.5m long fluid flow section is added at the inlet of the tube receiver.

The concentration ratio on the tube outer surface is simulated and shown in Fig. 3, whose elliptical cavity collector parameters are summarized in Table 1. As can be seen from the figure, there are two
concentration ratio peaks on one side of the tube receiver outer wall, which locate at 15° and 70°, respectively.

![Geometry and coordinate of the tube absorber.](image1.png)

![Concentration ratio on the tube outer surface.](image2.png)

**Table 1** Geometric parameters of the elliptical cavity collector.

| Parameter (Unit)                                      | Value     |
|------------------------------------------------------|-----------|
| Open width of the parabolic trough collector, \(d\)  (mm) | 2500      |
| Focal length, \(f\) (mm)                            | 850       |
| Major semi-axis of the elliptical cavity, \(b\) (mm)  | 64        |
| Minor semi-axis of the elliptical cavity, \(a\) (mm)  | 60        |
| Radius of the tube receiver, \(r\) (mm)             | 35        |

### 3. Results and Discussion

#### 3.1. Boundary conditions

The inlet temperature in the single-phase zone is set as 500K in the undercooling zone and 590K in the overheating zone. The inlet pressure is set as 10MPa and the inlet velocity is set as 0.5m/s. Reflectance of the parabolic trough mirror is 0.95 and the transmittance of the elliptical glass is 0.95. The reflectivity of the reflection layer of the cavity inner wall is 0.95, and the absorption rate of the surface of the tube receiver is 0.95. The thermo-physics parameters of water and vapor are obtained through REFPR OP (Reference Fluid Properties) software, which are introduced into Fluent software. Parameters of the tube absorber are shown in Table 2.

**Table 2** Properties of tube absorber.

| Parameter                              | Value             |
|----------------------------------------|-------------------|
| Specific heat                          | 502.48 J/(kg·K)   |
| Heat conductivity Coefficient          | 16.27 W/(m·K)     |
| Density                                | 8030 kg/m³        |
| Elastic modulus                        | 2×10¹¹ Pa         |
| Poisson ratio                          | 0.3               |
| Expansion coefficient                  | 1.5×10⁻⁵ K⁻¹      |

#### 3.2. Model validation

In order to verify the correctness of the method used in this paper, the numerical simulation is carried out to compare with the results reported in the literature [12], whose inlet temperature, inlet pressure and inlet mass flow rate are 573K, 6MPa and 0.56kg/s, respectively. The simulated results in the literature and using the present method are compared in Fig. 4. As can be seen from the figure, the temperature distribution obtained by the method used in this study matches well with the reported results in the literature, whose maximum temperatures are both 621K, and high temperatures both locate at outer wall of the lower half tube.
3.3. Heat flux distribution under different elliptical cavity geometry

The influence of major semi-axis of the elliptical cavity is first analysed, when the opening width and focal length of the parabolic trough and short semi-axle of the elliptical cavity are 2500mm, 850mm and 60mm, respectively. When the major semi-axis $b$ varies between the interval [62.5, 68.9], the heat flux distribution on the outer wall of the tube receiver is shown in Fig. 5.

![Graph showing heat flux distribution](image)

**Fig. 5** Flux distribution of absorber tube.

3.4. Temperature distribution under different elliptical cavity geometry

Fig. 6 shows the temperature distribution of the absorber tube in the undercooling zone of the elliptical cavity collector tube at the position of 500mm, when the opening width of the parabolic trough collector is 2500mm, the focal length is 850mm, and the minor semi-axle of the elliptical cavity is 60mm. It can be seen from Fig. 6 that the temperature rise of the tube receiver is mainly divided into three locations, which are at 0°, 60° and 300° of the tube receivers respectively. With the increase of $b$ (major semi-axis), the maximum temperature of the tube receiver decreases gradually. When $b = 63$mm, the maximum temperature of the tube receiver reaches its maximum. And it is concentrated at the position of -35mm of the tube receiver, that is, the position of the tube receiver at 0°. As $b$ continues to increase, the temperature distribution of the tube receiver shifts towards 60° and 300°. When $b \geq 66$mm, the temperature distribution basically maintains as $b$ increases. It can also be seen from the Fig. 6 that the temperature of the tube receiver is the highest near the outer wall. The closer it is to the inner wall of the tube receiver, the lower the temperature of the tube receiver would be. And on the side without incident heat flux, the temperature of the tube receiver is almost the same as the inlet temperature due to the thermal conduction of the tube receiver and the heat convection of the internal fluid.
Fig. 6 Temperature distribution on the absorber tube under different major semi-axis lengths (unit: K).

Fig. 7 shows the temperature distribution of the cross-section of the absorber tube at the position of 500mm, when the opening width of the parabolic trough collector is 2500mm, the focal length is 850mm and the minor semi-axis $a$ is 60mm. The inner fluid is under the liquid phase. As can be seen from the figure, the temperature distribution of the tube absorber and the heat flux distribution tend to be consistent, with two extreme locations. When $b = 63$mm, the highest temperature locates at (-35mm,
0mm), with the maximum temperature $T_{\text{max}} = 539.27$ K, where temperature rises is $39.27$ K. The other extreme location is at (-9mm, 0mm), and the temperature is $504.17$ K. As $b$ continues to increase, the maximum temperature drops rapidly. When $b = 66$ mm, the maximum temperature drops gently, but the maximum temperature is always at (-35mm, 0mm). When $b = 67$ mm, the highest temperature is at the position of (-15mm, 0mm), and the maximum temperature $T_{\text{max}} = 508.694$ K. At this time, the minimum temperature rises to $8.694$ K. The other extreme point is at (-34.4mm, 0mm), and the temperature is $507.163$ K. As $b$ continues to increase, the increase of temperature is less than 1% when $b = 68$ mm.

**Fig. 7** Temperature distribution on absorber tube in liquid region.

Due to the low temperature and high density of water in the supercooled area, the temperature rise is not obvious. In the superheated region, the vapor has a high temperature and pressure. The temperature distribution of the cross-section of the absorber tube when the inner fluid is vapor is then analysed, whose results are shown in Fig. 8. As can be seen from the figure, when $b = 63$ mm, the highest temperature is at (-35mm, 0mm), the maximum temperature $T_{\text{max}} = 725.85$ K, and the maximum temperature rise is $135.85$ K. Compared with the liquid phase, the maximum temperature rise is increased by $245\%$. The other extreme location is at (-7mm, 0mm), and the temperature is 598.503 K. As $b$ continues to increase, the maximum temperature drops rapidly. When $b = 66$ mm, the maximum temperature drops gently, but the maximum temperature is always at (-35mm, 0mm). When $b = 67$ mm, the maximum temperature reaches the minimum value, $T_{\text{max}} = 620.374$ K, and the minimum temperature rise is 30.374K, which is 3.5 times of the minimum temperature rise in the undercooling zone. The maximum temperature is at (-13.88 mm, 0mm). The other extreme location is at (-34.4 mm, 0mm), and the temperature is 620.102 K. As $b$ continues to increase, the temperature rises slowly. When $b = 68$ mm, the temperature rise is less than 0.5%.

As can be seen from Figs. 7 and 8, the temperature distribution of the supercooled zone and the superheated zone is the same. But the temperature rise of the superheated zone is much larger than that of the supercooled zone. Moreover, due to the high temperature rise of the gas phase in the superheated zone, the tube absorber also has a certain temperature rise on the side without heat flux.

**Fig. 8** Temperature distribution on absorber tube in vapor region.
4. Conclusions
The elliptic cavity tube absorber in the parabolic trough solar collectors has high optical and thermal efficiencies. But the asymmetric temperature distribution on the elliptic cavity tube absorber will cause non-uniform thermal stress and deformation. The temperature distribution of the absorber tube in the single-phase zones of the parabolic trough solar collector is thus analysed in study. It is found from this study that:
(1) There are two extreme temperature locations in the elliptical cavity tube receiver.
(2) When \( b \) (major semi-axis) = 63mm, the maximum temperature of the water zone is the largest, which occurs at (-35mm, 0mm) of the tube receiver, and the temperature rise is the largest.
(3) When \( b = 67 \)mm, the maximum temperature appears at (-9mm, 0mm), and the minimum temperature rise appears at (-13.88mm, 0mm) in the vapour zone.

Acknowledgments
This research was funded by the Natural Science Foundation of Jiangsu Province [No.: BK20201161], the National Natural Science Foundation of China [No.: 51506043], and the Fundamental Research Funds for the Central Universities [No.: B210202128].

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