Renewable Energy 93 (2016) 525–535

Contents lists available at ScienceDirect

Renewable Energy

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

# Optimal energy use of the collector tube in solar power tower plant

Ting Ren [a], Yang Sun [a], Jiye Zhang [b], Gaocheng Yan [a], Huaiping Mu [a], Shi Liu [a, b, *]

[a] School of Energy, Power and Mechanical Engineering, North China Electric Power University, Changping District, Beijing 102206, China
[b] School of Control and Computer Engineering, North China Electric Power University, Changping District, Beijing 102206, China

A R T I C L E I N F O

*Article history:*
Received 26 November 2015
Received in revised form
18 February 2016
Accepted 26 February 2016
Available online 15 March 2016

*Keywords:*
Heat transfer
Exergy transfer
Optimization
Energy use
Gravitational search algorithm

A B S T R A C T

As one of the most important parts of the solar power tower plant, the receiver plays an important role in the high-efficiency operation of the solar power tower system. Obtaining the maximum available energy in the receiver is highly desired in real-world operations. In this paper heat transfer and exergy transfer methods are used to model the energy transfer process in a collector tube. Different from common analysis methods, in order to ensure the molten salt to obtain the maximum available energy, an objective function is proposed to convert the task into a constrained optimization problem. The gravitational search (GS) algorithm is employed to search for the optimal solution of the proposed objective function. Numerical results indicate that the proposed optimization method can find the optimal operation parameters under different conditions. The heat transfer and exergy transfer characteristics along the collector tube under the optimal working condition are revealed, which quantifies the available energy along the collector tube, as well as reveals the location of energy degradation in the tube. The research findings will provide a beneficial reference for the effective use of the solar energy.



## 1. Introduction

The solar power tower technology is considered to be a promising option for reducing the pollutant emission and alleviating the energy crisis [1–8]. The solar power tower plant using molten salt as a heat transfer fluid has several appealing advantages, e.g., high working temperature, high efficiency, greater power, etc. As one of the most important parts of the solar power tower system, the receiver consists of several collector tubes, and converts solar radiation into heat energy. As a result, the energy use efficiency of the receiver plays a crucial role in the high-efficiency operation of the solar power tower plant.

Two approaches, e.g., the heat analysis method and the exergy analysis method, have been developed for assessing the energy use efficiency of the collector tubes. According to the heat analysis method, Boudaoud et al. [9] investigated the solar power plant capacity on the thermal efficiency, and the results indicated that the hybrid molten salt solar power tower technology is promising. From the viewpoint of the heat transfer, in order to improve the heat transfer performances, Montes et al. [10] estimated the optimal width of each module of the active surface, as well as the tubes diameter and thickness of each of them. In order to investigate the effect of rotation on natural convection losses that can influences the efficiency of the solar power receiver, an electrically heated rotating cavity was designed and built up by Wu et al. [11]. According to the first law of thermodynamics, Boerema et al. [12] investigated the effect of several engineering concepts on the resultant surface temperatures of tubular billboard receivers. Lu et al. [13] optimized the exergy efficiency of the receiver in a solar thermal power system by considering the heat loss outside the receiver and fluid viscous dissipation inside the receiver. Xu et al. [14] carried out the energy and exergy analysis of the receiver system in a solar power tower plant. They evaluated the energy and exergy losses in each component and in the overall system to identify the causes and locations of the thermodynamic imperfection. Experimental investigations on the energy and exergy performances of a coiled tube solar receiver were carried out by Zhu et al. [15]. The study results indicate that the highest exergy efficiency is approximately 28% and the highest energy efficiency is around 82%. However, in previous studies the research objective was often considered as a black-box model, without the consideration of the detailed information along the receiver. Furthermore, the exergy efficiency in the solar receiver is optimized to reaches to the maximum value under several predetermined conditions,

* Corresponding author. School of Energy, Power and Mechanical Engineering, North China Electric Power University, Changping District, Beijing 102206, China.
*E-mail addresses:* renting0203@126.com (T. Ren), sunyang@ncepu.edu.cn (Y. Sun), zhangjiye2012@gmail.com (J. Zhang), yangaochengbox@163.com (G. Yan), woodengoal@126.com (H. Mu), lssubmission@126.com (S. Liu).

http://dx.doi.org/10.1016/j.renene.2016.02.074
0960-1481/

which do not well match the real-world conditions.

With the framework of the heat transfer method and the first law of thermodynamics, the heat analysis method is employed to calculate the efficiency of the energy use in practical applications. The energy efficiency describes the quantity of the energy transfer and conversion, which is considered to be an important criterion for assessing the energy use efficiency. Compared with the energy analysis method, the exergy analysis method overcomes the limitations of heat analysis method. Furthermore, the exergy analysis method can reveal the locations of energy degradation and contribute to understanding the energy losses by providing more meaningful information than the energy analysis method. Different from the energy efficiency, therefore, the exergy efficiency is used to quantify the energy transfer and conversion processes.

According to the above discussions, a nature problem arises, i.e., is it possible to obtain the local details of quantity and quality of the energy transfer along a collector tube? Is it possible to acquire the maximum available solar energy? If the answers are yes, another critical problem will appear, i.e., how to achieve the goals? In this study, in order to obtain the maximum available energy in a collector tube, an objective function is proposed to convert the task into a constrained optimization problem. The GS algorithm is employed to solve the proposed objective function, and the optimal working condition is obtained. The results reveal the quantity and quality of energy transfer along the collector tube as well as the location of energy degradation in the tube, which are useful to understand and identify the irreversibility of the energy transfer process in the collector tube. The main contributions can be summarized as follows.

(1) The heat transfer and exergy transfer models are proposed to model the energy transfer process of the collector tube in the solar power tower plant, which provides a beneficial guide for the efficient use of solar energy.
(2) Different from common analysis methods, in order to make the molten salt to obtain the maximum available energy in a collector tube, an objective function is proposed to convert the task into a constrained optimization problem. The GS algorithm is employed to solve the proposed objective function.
(3) Numerical simulations under the optimal working condition are carried out to research the heat transfer and exergy transfer performances along the collector tube. The energy use efficiencies of the collector tube under different working conditions are revealed.

The remainder of this paper is organized as follows. Section 2, we introduce the mathematical models to describe the heat transfer and exergy transfer processes in a collector tube. In Section 3, an objective function is proposed to convert the exergy transfer method based efficient energy use task into an optimization problem, and the GS algorithm is used to seek for the optimal solution of the proposed objective function. In Section 4, the thermal performances of the collector tube are numerically investigated, and the results under several operating conditions are presented. Finally, the main conclusions are summarized in Section 5.

## 2. Model

The heat transfer analysis and exergy transfer analysis methods have found wide applications in the field of thermal engineering. In this section, we describe the heat transfer and exergy transfer processes in a collector tube.

In this study, one representative tube of the tubular solar receiver is chosen as the research object in this paper. The outside diameter of the collector tube is 0.021 m, the wall thickness is 0.0012 m and the tube length is 6 m. Molten salt (consisting of 60% $NaNO_3$ and 40% $KNO_3$) [16,17] is used as a heat transfer fluid, and the physical parameters are functions of temperature. The fluid flows upward to capture the solar radiation energy from the tube surface [16].

Heat and exergy can be transferred across the boundary of the collector tube, in which the heat transfer accompanies with the exergy transfer. The thermal performances of the collector tube had been intensively studied in the last decades [13–15]. Unfortunately, the exergy transfer of the tube was analyzed according to the black-box model. Different from previous investigations, this paper introduces the heat transfer and exergy transfer processes for describing the detailed behaviors of the available energy along the collector tube. Moreover, the energy use efficiency of the collector tube is employed as the optimization objective to obtain the maximum available energy. Before introducing the exergy transfer analysis method, the heat transfer analysis method is first presented, and more details can be traced back to [9–15].

### 2.1. Heat transfer

In the heat transfer model, the molten salt absorbs the solar energy accompanying with the heat loss by convection, radiation and reflection. Fig. 1 is the energy flow chart, which can be formulated as [18]:

$$Q = Q_{conv\_loss} + Q_{rad\_loss} + Q_{ref\_loss} + Q_{ms} \tag{1}$$

where $Q$ represents the solar radiation energy absorbed by the tube wall; $Q_{conv\_loss}$ defines the convection loss; $Q_{rad\_loss}$ stands for the radiation loss; $Q_{ref\_loss}$ is the reflection loss; $Q_{ms}$ represents the heat obtained by the molten salt.

The solar energy can be transferred to the molten salt by means of heat conduction, convection and radiation [18].

The outer wall converts the absorbed heat to the inner wall by conduction, thus the heat conduction in the wall is described as follows [19]:

$$Q_{cond} = \frac{2\pi\lambda l(T_{wo} - T_{wi})}{\ln(d_o/d_i)} \tag{2}$$

where $Q_{cond}$ defines the value of heat transfer by conduction; $\lambda$ represents the conduction coefficient of the tube wall; $l$ is the length of the study section; $T_{wo}$ and $T_{wi}$ stand for the temperatures

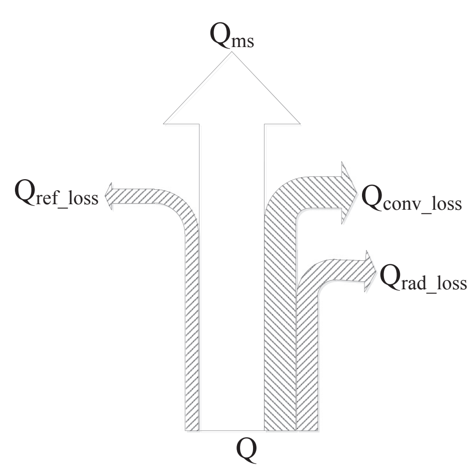


**Fig. 1.** Energy flow diagram of the collector tube.