Applied Thermal Engineering 70 (2014) 462–476

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

A three-dimensional simulation of a parabolic trough solar collector system using molten salt as heat transfer fluid

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HIGHLIGHTS

- A coupled three-dimensional simulation is established.
- The performance of the PTCs with molten salt as HTF was obtained.
- The effects of key parameters on the PTCs with molten salt were achieved.
- The coupling characteristics of thermal and fluid of the receiver were disclosed.

ARTICLE INFO

Article history:
Received 24 March 2014
Accepted 15 May 2014
Available online 23 May 2014

Keywords:
Solar energy flux distribution
Finite Element Method
Molten salt
Circumferential temperature difference
Numerical simulation

ABSTRACT

Investigations on the thermal physics mechanisms of the parabolic trough collector systems (PTCs) play a vital role in the utilization of solar energy. In this paper, a three-dimensional simulation based on Finite Element Method (FVM) is established to solve the complex problem coupling with radiation, heat conduction and convection in the PTCs. The performances of the PTCs using molten salt as the heat transfer fluid were numerically studied, and the influences of the key operating parameters on the PTCs were investigated. As a result, it can be found that the circumferential temperature difference (CTD) of the absorber increases with the rising of the direct normal irradiance (DNI) and decreases with the increase of heat transfer fluid (HTF) inlet temperature and inlet velocity. With the velocity of the molten salt in the range of 1 m/s–4 m/s, the DNIs of 500 W/m^2–1250 W/m^2 and the inlet temperature of 623 K –825 K, the CTD of the absorber can reach 12 K–42 K. Furthermore, the numerical results indicate the non-uniform distribution of the solar energy flux affects the CTD of receiver while has a little influence on the thermal efficiency. The promising results will provide a reference for the design of the novel parabolic trough solar collectors.

1. Introduction

Owing to the advantages such as clean, sustainability and inexhaustibility, solar energy is considered as a promising renewable energy. Among the solar power technologies, the parabolic trough solar technology is one of the most mature and cost-effective power technologies presently [1]. Using molten salt as the heat transfer fluid (HTF) is promising in the parabolic trough solar power plants owing to the distinct advantages such as high thermal capacity and low cost.

The heat collecting element (HCE) plays a crucial role in the parabolic trough collector system (PTCs), which has been studied intensively. In the past years, the investigations on the heat transfer models of the HCE often assume the uniform temperature distribution around the receiver's circumference, and neglect the influences of the non-uniform distribution of solar energy flux on the receiver [2–7]. Recently, the authors in Ref. [8] reported three dimensional numerical simulation results of the HCE when the non-uniform distributions of solar energy flux are considered. Cheng et al. reported a numerical simulation of a parabolic trough solar collector with non-uniform solar flux conditions by coupling the finite volume method and the Monte Carlo ray-trace method, in which the effects of the properties of different HTFs on the whole temperature distributions in the receiver, the thermal loss and the collector efficiency were studied [9]. The influences of the DNI,

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http://dx.doi.org/10.1016/j.applthermaleng.2014.05.051
1359-4311/

Reynolds number and the emissivity of the inner tube wall on the outlet temperature, average temperature of the absorber outer wall, thermal radiation loss and efficiency were investigated [10], and the concentrating characteristics of the PTCs were discussed [11]. Additionally, experimental studies on the PTCs systems were also carried out [12–15]. Owing to the complexities and particularities, of the problem, generally, the investigations on parabolic trough solar power plants using molten salt as the HTF are far from perfect.

In order to reveal the influences of the non-uniform distributions of the solar energy flux on the performance of the PTCs systems, the key issue of the influences of the non-uniform distributions of the solar energy flux is studied, and the main contributions can be summarized as follows:

(1) In order to reveal the thermal and fluid characteristics of the HCEs, a three-dimensional numerical simulation on the PTCs system is implemented. The solar energy flux profile was calculated by the ray-tracing method, and performance simulations with a motivation of analyzing the process of converting solar radiation to solar thermal energy for a PTCs system are implemented by the Finite Element Method (FEM).
(2) The effects of the key operating parameters on the performance for the HCEs are investigated, and the relationships of the circumferential temperature difference (CTD) with the DNI, the HTF inlet velocity, the HTF's inlet temperature, and the thermal and fluid characteristics of the collector are found.
(3) A comparison is made between two types of typical HTFs to investigate the influence on the performance of the PTCs system. The influence of non-uniform distribution of the solar flux on the performance of the HCEs is also studied. The research findings will provide a reference for the design of the parabolic trough solar collectors.

2. Heat collecting element model

Using the molten salt as a HTF in a trough plant has several obvious advantages. First of all, it can increase the solar field output temperature to 723–823 K, and thus the Rankine cycle efficiency is increased. Moreover, the molten salt is cost-effective and more environmentally friendly than the synthetic oil. The major disadvantage of the molten salt is that the molten salt has high melting point, leading to complicated freeze protections in the solar field. In this paper, a mixture of salts (a binary salt consisting of 60% $NaNO_3$ and 40% KNO_3) was used, in which the working temperature limit is about 873 K and the freezing point is about 493 K.

An experimental solar collector platform of 600 m^2 solar field with the thermal power of about 300 kW was built in Langfang city by Institute of Engineering Thermophysics, Chinese Academy of Sciences. The solar collector, which is shown in Fig. 1, is chosen as the physical model in the simulations, and the physical parameters are listed in Table 1.

Table 1
Receiver dimensions shown in Fig. 1.

Focal length	1.71 m
Aperture width	5.77 m
Receiver length	4 m
Material of the steel pipe	Electric-welded AISI 316Ti steel
Absorber inner radius	3.2 cm
Absorber outer radius	3.5 cm
Material of the glass pipe	Borosilicate glass
Transmittance of the glass pipe	>96%
Cover inner radius	5.95 cm
Cover outer radius	6.25 cm
Coating absorbance	95%
Coating emissivity	10% at 673 K; 14% at 823 K; 15% at 853 K
Min/max operating temperature of the molten salt mixture	563 K/823 K
Maximum operating temperature of receiver tube	853 K

3. Performance simulations of a PTC system

3.1. Non-uniform solar energy flux calculation

To set up a more realistic three-dimensional model, the accurate calculation of realistic non-uniform solar energy flux distribution of the PTCs system is necessary. The ray-tracing method is an efficient numerical method to simulate the focus process of the sun rays. SolTrace is a software tool developed by the National Renewable Energy Laboratory (NREL) to model concentrating solar power optical systems and analyze their performances. The code has been compared with earlier modeling results and actual optical measurements, and has demonstrated good agreement with both [16].

Firstly the sun was defined by using a pillbox sun shape with 4.65 mrads. Then the geometry model of the collector according to the PTCs system shown in Table 1 was set up, and the properties of each component, such as the reflectivity and transmissivity, are set. In this paper, for easy computation, the collector length is chosen as unit length, the number of rays traced is 1×10^5 when the DNI is 1000 W/m^2.

Fig. 2 is the simulation results of the local concentration ratio (LCR) distribution on a cross-section of the absorber outer surface. The LCR is defined as the ratio of the concentrated radiant flux at a local position on the receiver surface to the incident beam normal irradiance. It can be observed from Fig. 2 that the solar energy flux distribution is symmetrical approximately, and the solar energy flux in the circumferential direction is non-uniform. The non-uniform solar energy flux distribution will lead to non-uniform circumferential temperature distribution, which brings

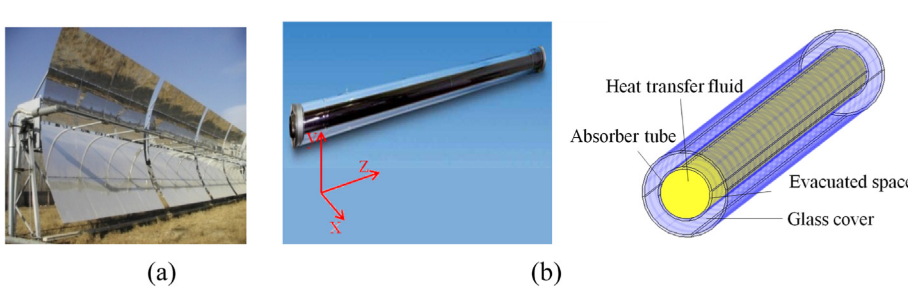

Fig. 1. (a) Experiment platform with 600 m^2 in Langfang city. (b) Schematic of the parabolic trough solar receiver.