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Performance analysis of a parabolic trough solar collector with non-uniform solar flux conditions

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ABSTRACT

The improvement of the performances of the parabolic trough solar collector system (PTC) plays a vital role in the utilizations of solar energy. In this paper, a solar ray trace (SRT) method and the finite element method (FEM) based numerical simulation method is proposed to solve the complex problem coupled with fluid flow, heat transfer and thermal stress in a PTC system. The profile of the solar energy flux is calculated by the SRT method, and the effects of the key operating parameters on the performances of the receiver are numerically investigated. The distributions of the stress intensity and the thermal deformations of the receiver are numerically studied. Numerical simulation results indicate that the circumferential temperature difference (CTD) of the absorber decreases with the increases of inlet temperature and velocity of the heat transfer fluid (HTF) and increases with the increment of the direct normal irradiance (DNI). When the inlet velocity is in a range of 1.00–4.00 m/s, the DNIs are 500–1250 W/m^2 and the inlet temperature is 373–673 K, the CTD of the absorber can reach 22–94 K. The thermal stress and the deformations of the absorber are higher than that of the glass cover. The promising results will provide a fundamental reference for the development of the parabolic trough solar thermal power plant in China.

1. Introduction

With the depletion of fossil fuels and greenhouse effect, the utilization of solar energy has attracted increasing attention owing to the distinct advantages, including clean, sustainability, inexhaustibility, etc. Among the three main solar thermal power generation systems, including the parabolic trough, the central receiver and the parabolic dish, the parabolic trough solar technology is the most proven and cost-effective, large-scale solar power technology available today [1].

The parabolic trough linear receiver, which can also be called as the HCE, is a key component in a parabolic trough collector system. Presently, the key issues on improving the performances of the HCE have obtained wide attention, and thus numerous studies have been implemented. García-Valladares et al. investigated different influences of the HCE geometric structures on the HCE and found that the double-pass can increase the thermal efficiency of the PTC system, improve the heat transfer and reduce the environment thermal losses with the increase of the recycle ratio, channel thickness ratio and Reynolds number [2]. Naeeni et al. studied the influence of the wind on the parabolic collector. A two-dimensional numerical simulation of turbulent flow around a parabolic trough collector is implemented to exploit the effects of variation of collector angle of attack, wind velocity and its distribution with respect to height from the ground. They found that the effect of the absorber tube on the flow field was negligible, while the influences of the gap between the two sections of the parabola at midsection and the gap between the collector and ground on the flow field and the pressure distribution around the collector were considerable [3,4]. Bader et al. proposed a novel solar trough concentrator design of a cylindrical cavity-receiver containing a tubular absorber that uses air as the heat transfer fluid. A two-dimensional steady-state numerical heat transfer model was developed to determine the absorption efficiency of the receiver and the requirement of the pumping power. As mass flow rate of the air was varying in the range 0.1–1.2 kg/s, the absorption efficiencies is increased to 60% from 18%, and the isentropic pumping power requirements increased to 1.14 W from 1.9 W [5]. Liu et al. developed the least squares support vector machine method to model and optimize the parabolic trough solar collector system, which has a remarkable advantage of fast predicting the performances

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of the solar collector and identifying the optimal operation parameters [6]. Recently, Cheng et al. reported a three-dimensional simulation of a parabolic trough solar collector with non-uniform solar flux conditions by incorporating the FVM and the MCRT method, in which the effects of the properties of different HTFs to the whole temperature distributions in the receiver, the thermal loss and the collector efficiency were numerically studied [7]. Moreover, the effects of the DNI, Reynolds number and emissivity of the inner tube wall on the outlet temperature, average temperature of absorber outer wall, thermal radiation loss and efficiency [8], and the concentrating characteristics of the parabolic trough solar collectors PTCs [9] were discussed. Additionally, experimental studies on the parabolic trough collector systems were also implemented [10–13].

The failure of the glass-to-metal seal is a main reason of damage to the HCE, 30%-40% of the receivers failure occurred at SEGS VI–IX for 9–11 years of operation, which is derived from the concentrated flux hitting the glass-to-metal seal [14,15]. Due to the non-uniform distributions of the solar energy flux, there exist CTD of the absorber and the cover, which has a crucial influence on the circumferential stress and the deformation of the receiver tubes. Lei et al. had made experimental study of glass to metal seals for the parabolic trough receivers, they presented a new method that uses the high-frequency induction heating to band a new borosilicate glass to the Kovar alloy ends, and thus a new solar receiver was developed. They also analyzed the residual stress in glass-to-metal seals for the solar receiver tube, and found that the maximum tensile stress happened near the sealing interface on the outer surface of glass tube. The seal strength increases with the augment of the thickness of the glass tube [16–18], while the influences of the non-uniform distribution of the solar energy flux on the glass-to-metal seals are omitted.

In this paper, a three-dimensional thermo-mechanical coupling model was implemented to investigate the effects of temperature on the deformation of the HCEs under non-uniform distribution of the solar flux. The influences of the non-uniform distribution of the solar energy flux on the thermal, fluid and structural characteristics of the HCEs are numerically studied, and the main contributions are summarized as:

(1) The solar energy flux profile was calculated by the SRT method, performance simulations with a motivation of analyzing the process of converting the solar radiation to solar thermal energy for a PTC system were implemented.
(2) The thermal and fluid characteristics of the HCEs are numerically obtained. The influences of the key operating parameters on the performances of the HCEs were investigated, including the relationships of the CTD with the DNI, the HTF inlet velocity and the HTF inlet temperature.
(3) The distributions of the stress intensity and the CTD deformation of the receiver were numerically acquired, and the characteristics of the distributions were presented, which will facilitate to ensure the safety of the PTC system.

The rest of the paper is structured as follows. The parabolic trough collector model is introduced in Section 2. The performance simulations of a PTC system are implemented in Section 3. The numerical results and detailed discussion on the results is given in Section 4. Finally, Section 5 summarizes the main conclusions.

2. Parabolic trough collector model

An experimental solar collector platform of 600 m^2 solar field with the thermal power of about 300 kW was built in Langfang city, Hebei Province, China. The solar collector is chosen as the physical model for the simulations. The parameters of the solar collectors are shown in Table 1. Fig. 1 shows the experiment platform and the schematic of the parabolic trough solar receiver. The one-tracking parabolic trough concentrator are positioned in a south–north direction. Dowtherm A synthetic oil is chosen as the heat transfer fluid. Dowtherm A heat transfer fluid is a eutectic mixture of two very stable organic compounds, biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$). Its normal application range is 288.15–673.15 K. It does not decompose readily at high temperatures, and can be used effectively in either liquid or vapor phase systems [19].

It can be seen from Fig. 1 that the collector consists of a receiver and a reflector. The reflector curved in one axis to focus the sun rays. The receiver consists of a cylindrical glass envelope containing an eccentric absorber tube with vacuum in the space. The absorber tube is plated with a selective coating, in which the coating is designed to allow pipes to absorb high levels of the solar radiation while emitting very little infrared radiation. The physical parameters are listed in Table 1.

3. Performance simulations in a PTC system

3.1. Non-uniform solar energy flux distribution

Acquiring the high-quality flux distributions in a PTC system plays a crucial role in establishing an appropriate three-dimensional numerical model. Owing to the advantages, including easy numerical implementation and high computational efficiency, in this paper the ray-tracing method is employed to simulate the focus process of the sun rays. In this work, the SolTrace software is employed to compute the solar energy flux [20].

In simulations, the sun is firstly defined by using a pillbox sun shape with 4.65 mrads, and then the geometry model of the collector, which is presented in Table 1, is defined. Particularly, the properties of each component, including the reflectivity and transmissivity, are predetermined. For the sake of illustrating the model and simplifying the problem, the length of the receiver is adopted unit length of 1 m, the DNI is 1000 W/m^2, and the number of rays traced is 1×10^5. The rays come from the sun firstly encounter the absorber and reflector probabilistic, and the rays that encounter to the reflector are reflected to the absorber and absorbed by it. Some of rays that do not encounter the reflector and the absorber were lost, as shown in Fig. 2a and b. The yellow lines represent the sun's rays and each dot stands for a ray intersection.

Fig. 3 shows the cross-section irradiation profile on the outer surface of the absorber generated by the SolTRACE software. It can be observed from Fig. 3 that the solar energy flux distribution is symmetrical approximately, and the temperature distributions in the circumferential direction are non-uniform, and the highest solar flux is about 55 kW/m^2 at the bottom part of the absorber, while the lowest solar flux is about 1 kW/m^2 at the top part of

Table 1
Physical parameters of the receiver.

Focal length	1.71 m
Aperture width	5.77 m
Rim angle	80.2°
Concentration ratio	82
Mirror reflectivity	0.94
Material of the steel pipe	TP304H steel
Absorber inner diameter	6.50 cm
Absorber outer diameter	7.00 cm
Material of the glass pipe	Borosilicate glass
Cover inner diameter	10.90 cm
Cover outer diameter	11.50 cm
Transmittance of the cover	0.96
Coating absorbance	0.95
Coating emissivity	$0.04795 + 0.0002331T$ [°C]