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Parabolic trough receiver with corrugated tube for improving heat transfer and thermal deformation characteristics

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HIGHLIGHTS

- Symmetric outward convex corrugated tube is introduced as the metal tube of PTR.
- Effective heat transfer coefficient can be increased up to 8.4% when SCPTR is used.
- Regression equation is put forward for heat transfer coefficient and Nusselt number.
- Corrugated tube can enhance thermal performance and reliability of PTR effectively.

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ABSTRACT

A symmetric outward convex corrugated tube design is introduced for parabolic trough receivers with the aim of increasing their heat transfer performance and reliability. An optical–thermal–structural sequential coupled method was developed to analyze the heat transfer performance and thermal deformation of the glass cover and metal tube of the parabolic trough receiver. The developed coupled method has been validated with experimental results conducted in the DISS test facility in Spain. The numerical results indicated that the introduction of a symmetric outward convex corrugated tube design for the metal tube of the parabolic trough receiver can effectively enhance the heat transfer performance and decrease the thermal strain. The effective heat transfer coefficient can be increased up to 8.4% and the maximum thermal strain of metal tube can be decreased up to 13.1% when symmetric outward convex corrugated tube is used at $Re = 81728$, $p/D = 4.3$. In addition, regression correlations are put forward in order to find an effective heat transfer coefficient and effective Nusselt number for the fluid flow in the parabolic trough receiver.

1. Introduction

Because of the continuous increase in CO_2 emissions and the shrinking of conventional energy supplies, there is a great demand for clean and renewable energy for meeting our energy needs [1,2]. Solar energy is the largest available carbon-neutral energy source, and is provided at nearly twice the Earth's consumption rate of fossil energy [3]. For solar thermal power generation, the use of highly concentrated solar irradiation provides lower heat losses from smaller areas and consequently higher attainable temperatures at the receivers [4–6]. Large-scale concentrated solar power is mainly based on four types of optical collectors: parabolic trough collectors (PTC), parabolic dish collectors, heliostats, and linear Fresnel reflectors (LFR) [7–10]. By using optical collectors, sunlight is redirected, collected, and focused as a high temperature heat source to power a Stirling engine or steam turbine in order to generate electricity [11,12].

Among the four optical collectors, solar thermal power plants (STTPs) with PTC technology have achieved commercial application for several decades because of the advantages of high power plant efficiency and low production cost [13,14]. For example, most of the new STPPs built in Spain are of PTC technology [15,16]. For STPPs with PTC technology, the evacuated metal tube with a glass cover (or a glass envelope) when used as parabolic trough receiver (PTR) is the critical component for converting the concentrated solar irradiation into heat by conductive and convective coupled heat transfer [17–20].

The bottom periphery of the PTR is subjected to concentrated solar radiation and the heat flux distribution is highly non-uniform. Whereas the top periphery of the PTR is subjected to low energy density solar irradiation. Therefore, the heat flux

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Nomenclature

C_p	heat capacity, J/(kg K)
D	diameter, m
g	gravity, m/s^2
h	heat transfer coefficient, W/(m^2 K)
R	radius, m
Re	Reynolds number
Nu	Nusselt number
q	heat flux, W
P	pressure, Pa
Pr	Prandtl number
T	temperature, K
r	radius, m
v	velocity, m/s
z	coordinates, m

Greek symbols

φ	circumferential angle, °
ρ	density, kg/m^3
ε	thermal stress, Pa
δ	thermal strain
λ	conductivity, W/(m K)
σ	thermal strain
δ	deviation

Subscripts

a	average temperature
exp	experiment
f	fluid
in	fluid inlet
t	top
k	the *k*th surface
cal	calculated
G	glass cover
b	bottom
eff	effective
MT	metal tube
$W–F$	wall to fluid
dim	dimensionless

distribution on the periphery of the PTR is highly non-uniform, which could induce large thermal deformation [21–23]. Due to the large thermophysical and structural property differences between the metal tube and the glass cover, there can be large thermal deformation differences along the longitudinal direction during operation which can induce a rupture in the glass cover [24,25]. As an example, the stainless steel PTRs in the STTPs at the National University of Mexico have experienced frequent deformations and glass cover ruptures during testing and application [26,27].

Until now, two main methods have been adopted to increase the reliability of PTRs: (1) homogenizing the temperature distribution and (2) improving the structure of the PTR. Because thermal deformations of the PTR are induced by temperature gradient, homogenizing the temperature distribution on the PTR can effectively minimize the thermal strain and deformation, especially for the metal tube. The temperature gradient on the metal tube can be decreased if the heat transfer performance inside the metal tube increase which can benefit for homogenize the temperature profile of metal tube. Huang et al. [28] and Muñoz et al. [29,30] adopted a helical internal fin design within the metal tube to enhance the convection heat transfer performance with the drawback of an increased pressure drop. Cheng et al. [31] proposed a unilateral multi-longitudinal vortex enhanced PTR to increase the overall heat transfer performance while reducing the peak temperature and temperature gradient of the metal tubes. A design using a nano-fluid was introduced and used in PTRs in order to increase the overall heat transfer coefficient and to homogenize the temperature distribution [32–35]. Diogo et al. adopted a secondary reflector as a homogenizing reflector for the PTR in order to homogenize the solar flux distribution, which in turn can decrease the thermal stress on the PTR [36].

In addition, some researchers have focused on improving the structure of tube receivers to increase the reliability of PTRs. The National University of Mexico [26] adopted bimetallic Cu–Fe tube receivers to reduce the temperature gradient and thermal deformation of the PTR. Wang et al. proposed using an eccentric design for the metal tube of the PTR in order to increase reliability. A coupled analysis method based on the Monte Carlo Ray Tracing (MCRT) method and the finite element method (FEM) was developed to analyze the thermal stress on the PTR. The numerical results indicated that adopting the eccentric tube design for the metal tube of the PTR can reduce the effective thermal stress by up to 41.1% [37,38].

Corrugated tubes have been widely used in various applications to enhance heat transfer performance by intermittently breaking the momentum and thermal boundary layers [39,40]. Fig. 1 shows the systematic outward convex transverse corrugated tubes fabricated through a hydraulic pressure method. The tubes were developed by the authors (Han et al.) for nuclear engineering devices for enhancing heat transfer [40]. However, to the best of the authors' knowledge, few researchers have adopted the corrugated tube design for the metal tube of PTRs.

In this study, a symmetric outward convex corrugated tube design is introduced for PTR (SCPTR) in order to enhance the heat transfer performance and increase reliability. It is a common sense that the glass cover rupture is caused by the large thermal deformation differences along the longitudinal direction between glass cover and metal tube, no detailed researches have been conducted to give a precise illustration. In this study, the thermal deformations of the glass cover and metal tube of the PTR are analyzed by the MCRT, FVM and FEM [41] sequential coupled analysis method. In addition, regression correlations are also put forward to find an effective Nusselt number of the fluid flow in the metal tube for both the PTR and SCPTR.

2. Physical model

The schematic diagram of the solar parabolic trough collector with tube receiver is presented in Fig. 2. As seen in the figure, the incoming solar rays are concentrated on the bottom periphery of the PTR by the solar parabolic trough collector. However, the top periphery of the PTR is subjected to non-concentrated solar radiation. The cross section sketch of the PTR is shown in Fig. 3. A metal tube, which is generally made of stainless steel, is coated with selective coatings to increase the solar spectrum absorption and to minimize infrared spectrum emittance. The metal tube is surrounded by a glass cover. The gap between the metal tube and glass cover is kept at a vacuum to minimize heat losses. The geometrical parameters of the PTR used in this study are listed in Table 1, which are the same as Refs. [42,43].