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Heat transfer performance enhancement and thermal strain restrain of tube receiver for parabolic trough solar collector by using asymmetric outward convex corrugated tube

Wang Fuqiang [a], Tang Zhexiang [a], Gong Xiangtao [a], Tan Jianyu [a, *], Han Huaizhi [b], Li Bingxi [c]

[a] School of Automobile Engineering, Harbin Institute of Technology at Weihai, 2, West Wenhua Road, Weihai 264209, PR China
[b] College of Power and Energy Engineering, Harbin Engineering University, 145, Nantong Street, Harbin, 150001, PR China
[c] School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, PR China

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ABSTRACT

With the aim to increase the overall heat transfer performance and reliability of tube receiver for parabolic trough solar collector system, asymmetric outward convex corrugated tube is introduced as the metal tube of parabolic trough receiver. An optical-thermal-structural sequential coupled method was developed to study the heat transfer performance and thermal strain of tube receiver for parabolic trough solar collector system. Heat transfer performance and thermal strain comparisons between conventional tube receiver and asymmetric outward convex corrugated tube receiver are conducted. The researches indicated that the usage of asymmetric outward convex corrugated tube as receiver can enhance the heat transfer performance and reduce the thermal strain effectively. By using asymmetric outward convex corrugated tube as receiver, the maximum enhancement of overall heat transfer performance factor is 148% and the maximum restrain of von-Mises thermal strain is 26.8%.

1. Introduction

Global environmental degradation is one of the serious threats facing humankind as a result of its consuming of fossil fuel energy around the world [1,2]. The compatible development of both the efficient energy utilization and environment protection is the hottest issue in the 21st century [3]. Solar resource is the world's most abundant source of energy with the potential to meet a significant portion of the world's energy requirements [4,5]. Solar energy is widely available and one of the renewable forms of energy with little impact on the environment [6]. Concentrated solar power technology is a technology which can be capable of producing clean, renewable and grid-scale energy [7,8]. Due to the present situation, the concentrated solar thermal power generation technologies have attracted increasing interests in the renewable energy fields [9]. These technologies are classified by their focus geometry as either point-focus concentrators (central receiver systems and parabolic dishes) or line-focus concentrators (parabolic-trough collectors, and linear Fresnel collectors) [10–14]. Among these technologies, parabolic trough solar thermal power technology has been widely adopted among these solar thermal power utilizations [15].

Parabolic trough type solar thermal power plant consists of parabolic trough collectors (PTC), parabolic trough receivers (PTR) with heat transfer fluid (HTF)/steam generation system, Rankin steam turbines/generator cycles, and optional thermal storage and/or fossil-fired backup systems [16]. The heat transfer fluid in the metal tube of PTR is heated by concentrated solar radiation [17–19]. The Chinese government had set up a research project in China 863 Program of "the research and demonstration of parabolic trough solar thermal power generation technology" during the National 12th Five-Year Plan, which aimed to develop the mass production technology of parabolic trough solar collector system [20].

The metal tube with evacuated glass envelop used as PTR is the key component where concentrated solar energy is converted to thermal energy [21]. The thermal strain caused by large

* Corresponding author.
E-mail address: Tanjianyu@hitwh.edu.cn (T. Jianyu).

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Nomenclature

A_{PTC}	Aperture of PTC, m
C_p	Heat capacity, J/(kg·K)
D	Diameter, m
f	Fanning friction factor
F_{PTC}	Focal length of PTC, m
G	Turbulent kinetic energy
H	Corrugation height, m
h	Heat transfer coefficient, W/(m^2 K)
K	Conductivity, W/(m K)
L_{PTR}	Length of PTR, m
Nu	Nusselt number
P	Pressure, Pa
p	Corrugation pitch
Pr	Prandtl number
q	Heat flux, W/m^2
R	Corrugation crest radius, m
Re	Reynolds number
r	Radius of tube receiver, m
rl	Large trough radius, m
rs	Small trough radius, m
S	Source terms
T	Temperature, K
v	Velocity, m/s
Y_M	Contribution of fluctuating dilatation

Greek symbols

α	Absorptivity of receiver
α_v	Coefficient of expansion
ρ	Reflectivity & Density, kg/m^3
μ	Dynamic viscosity, kg/(m s)
θ	Circumferential angle,°
θ_{par}	Non-parallelism angle, ′
θ_{rim}	Rim angle, °
σ_{mirror}	Mirror error, mrad
σ	Turbulent Prandtl number
Φ	Dissipation function
σ_{orient}	Pointing error, mrad
δ	relative error

Subscripts

a	Environment
b	Buoyancy
cal	Calculated
φ	Angle
exp	Experimental test
e	Envelope
f	Fluid
k	Mean velocity gradients
m	Metal tube
Max	Maximum temperature
Min	Minimum temperature
num	Numerical simulation
t	Time

temperature gradient during operation may cause bending of metal tube and rupture of glass envelope. The thermal deformations of PTR are related to the thermal conductivity of metal tube and glass envelop, flow pattern of HTF and asymmetry of the temperature distribution on the metal tube [22]. Wu et al. [23] had investigated the bending of stainless steel PTR by indoor experiments and numerical simulations and field measurements, and their researches indicated that the thermal deformation in the stainless steel tube changed inversely with HTF velocity and temperature. Lei et al. [24] indicated that the residual stresses were generated not only by the differences of the thermal expansion coefficients between the glass and the metal but also by the sealing geometry which had a significantly negative influence to the seal strength. It should be noted that an overlapped thermal strain of PTR for parabolic trough type solar thermal power plant would appear and vary with time during the operation.

It is a consensus that enhancing heat transfer performance in the PTR can reduce the temperature gradient which can results in less thermal deflections and improve the reliability of PTR. Aggrey et al. [25] had presented a new type of PTR with perforated plate inserting for parabolic trough solar collector to reduce the temperature gradient and peak temperature, their results indicated that the maximum reduction of temperature gradients in tube receiver was up to 33%. A new type of PTR with helical screw-tape inserting was proposed by Song et al. [26] to homogenize the temperature distribution on the metal tube of PTR and improve the thermal performance. Wang et al. [27] had investigated the effects of inserting metal foams in metal tube of PTR on heat transfer performance enhancement, and the results presented that the maximum circumferential temperature difference on the out surface of receiver tube decreases about 45% which can greatly reduce the thermal deformation of PTR.

Besides, optimizing the structure of PTR is also an effective way of reliability enhancement. Montes et al. [28] designed a new module that all the components are made of structural aluminum with the aim to decrease the thermal deformation and weight. With the aim to minimize heat flux gradient which in turn can reduce thermal deformation of tube receiver, glass cover with elliptic-circular cross section is put forward by Wang et al. [29]. Khanna et al. [30,31] had introduced the explicit expressions to obtain the temperature distribution of PTR and the corresponding deflections in the central axis of PTR, they also investigated the effects of desired rise in fluid temperature, optical errors and rim angle of PTC on temperature distribution and deflection of PTR with two types of structural constraints. He et al. [32–34] proposed to use milt-longitudinal vortexes and metal foam inserting in PTR to reduce temperature gradient and enhance the convective heat transfer with less pressure drop.

In the previous studies, the authors had introduced a symmetric outward convex corrugated tube for PTR to enhance the heat transfer performance, and an optical-thermal-structural sequential coupled method is developed to analyze the heat transfer performance and thermal deformation of glass envelope and metal tube of PTR [35]. The authors had also put forward an asymmetric corrugated tube for nuclear engineering devices for enhancing heat transfer [36]. Fig. 1 presents the asymmetric outward convex transverse corrugated tubes fabricated through a hydraulic pressure method. The authors had numerically investigated the flow and heat transfer characteristics of two tube types named as symmetric corrugated tube (SCT) and asymmetric corrugated tube (ACT), their investigation indicated that ACT can improve the overall heat transfer performance up to 18% over that of SCT [36].

Although the symmetric outward convex corrugated tube had been introduced as the metal tube of PTR and showed excellent