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Heat transfer enhancement analysis of tube receiver for parabolic trough solar collector with pin fin arrays inserting

Gong Xiangtao [a], Wang Fuqiang [a,*], Wang Haiyan [b], Tan Jianyu [a], Lai Qingzhi [a], Han Huaizhi [c]

[a] School of Automobile Engineering, Harbin Institute of Technology at Weihai, 2, West Wenhua Road, Weihai 264209, PR China
[b] Sionpec Star Petroleum Co., Ltd, No. 263, Xueyuan Street, Haidian District, Beijing 100083, PR China
[c] College of Power and Energy Engineering, Harbin Engineering University, 145, Nantong Street, Harbin 150001, PR China

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ABSTRACT

Tube receiver with pin fin arrays inserting was introduced as the absorber tube of parabolic trough receiver to increase the overall heat transfer performance of tube receiver for parabolic trough solar collector system. The Monte Carlo ray tracing method (MCRT) coupled with Finite Volume Method (FVM) was adopted to investigate the heat transfer performance and flow characteristics of tube receiver for parabolic trough solar collector system. To validate the feasibility of the developed MCRT and FVM combined method, the numerical results have been compared with experimental results conducted in the DISS test facility in Spain and the max relative error is less than 5%. The numerical results indicated that the introduction of absorber tube with pin fin arrays inserting design for the absorber tube of the parabolic trough receiver can effectively enhance the heat transfer performance. The average Nusselt number can be increased up to 9.0% and the overall heat transfer performance factor can be increased up to 12.0% when the tube receiver with pin fin arrays inserting was used.

1. Introduction

With the advantages of non-pollution, sustainability and inexhaustibility, solar energy, one of the earliest sources of energy for human beings, has been playing an increasingly vital role in the solution of energy crisis and the reduction of CO_2 emission today (Kribus et al., 2014; Mahian et al., 2014; Lei et al., 2010). Solar energy is collected from sunlight which is naturally replenished on a human timescale (Mwesigye et al., 2015; Cheng et al., 2014; Wang et al., 2016). Among all the methods of utilizing solar energy, concentrated solar power (CSP) technology is one of the promising and mature options, because the use of highly concentrated solar irradiation provides lower heat losses from smaller areas and consequently higher attainable temperature at the receivers (Barlev et al., 2011; He et al., 2015; Sarwar et al., 2015). Concentrating technologies exist in five common forms, namely parabolic trough collector (PTC), enclosed trough, parabolic dish collector (PDC), concentrating linear Fresnel reflector, and solar power tower. Among these technologies, the PTC technology has achieved commercial application for several decades due to the advantages of higher power plant efficiency and lower production cost (Padilla et al., 2011; Hachicha et al., 2013; Khanna et al., 2014).

A typical concentrated solar power plant with PTC technology is mainly composed by three modules: PTCs, parabolic trough receivers (PTR) and power generation devices (Xu and Wiesner, 2015; Wang et al., 2014b; Mao, 2016). The general structure of PTR is an absorber tube (made of metal) surrounded by a glass cover (also named glass envelope), while the annular gap between the absorber tube and glass cover is evacuated. In order to absorb the concentrated solar irradiation and decrease the thermal radiation losses effectively, a selective coating is coated on the outer surface of the absorber tube (Wu et al., 2014). The sunlight is collected and concentrated on the bottom periphery of PTR which is placed on the focal line of PTC, and then the concentrated solar irradiation is converted to heat and transferred by heat transfer fluid in the absorber tube to power steam turbine to generate electricity in turn (Cheng et al., 2015; Mwesigye et al., 2013). Parabolic trough systems have been in wide use for utility-grade power generation since the mid 1980s. The deployment, performance and operation of commercial, utility-grade parabolic trough solar thermal power plants are well-understood and proven. Parabolic trough plants are inherently modular and scalable. Modularity is important for achieving low cost through high volume production of components and subsystems. A parabolic trough solar field also has inherent "free" energy storage that, depending on the size of the plant, allows electricity production to continue well after the sun has been blocked by a cloud.

* Corresponding author.
E-mail address: Wangfuqiang@hitwh.edu.cn (F. Wang).

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Nomenclature

A	PFAI-PTR
A_{PTC}	aperture of PTC, m
CR	concentration ratio
C_p	heat capacity, J/(kg·K)
D	diameter of receiver, m
E_{sun}	solar irradiance, W/m^2
f	fanning friction factor
F_{PTC}	focal length of PTC, m
G_k	generation of turbulent kinetic energy due to the mean velocity gradients
G_b	generation of turbulent kinetic energy due to buoyancy
h	heat transfer coefficient, W/(m^2·K)
L_{PTR}	length of PTR, m
M	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
q	heat flux, W
Re	Reynolds number
S	smooth tube
S_k and S_ε	user-defined source term
T	temperature, K
V	velocity, m/s
Y_M	contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

Greek symbols

α	absorptivity of receiver
α_v	coefficient of expansion
ρ	reflectivity & density, kg/m^3
σ_ε	turbulent Prandtl numbers for ε
σ_k	turbulent Prandtl numbers fork
μ	dynamic viscosity, kg/(m·s)
θ	circumferential angle, °
θ_{par}	non-parallelism angle, ′
θ_{rim}	rim angle, °
σ_{mirror}	mirror error, mrad
σ_{orient}	pointing error, mrad
Φ	dissipation function

Subscripts

a	environment
cal	calculated
Exp	experimental test
g	glass envelope
f	fluid
m	absorber tube
Max	maximum temperature
Min	minimum temperature
Num	numerical simulation

The bottom periphery of PTR is subjected to concentrated solar irradiation, while the top periphery of PTR is subjected to solar irradiation with low energy density. Therefore, the heat flux distribution on the periphery of PTR is highly non-uniform, which can result in high temperature gradients. The large thermal strain, induced by high temperature gradients, can cause the thermal deformations of absorber tube and glass envelop. Due to the large thermophysical and structural properties differences between metal and glass, the thermal deformation differences between absorber tube and glass cover can induce the rupture of the glass cover (Khanna et al., 2013; Patil et al., 2014). Therefore, the PTR of parabolic trough solar power system is prone to failure during application. For example, the first nine large commercial-scale parabolic trough solar plants located in Mojave Desert had experienced an unacceptable high failure rate of the PTR during the first few years. According to the recorded data, the average annual PTR replacement rate was still 5.5% (Assessment of parabolic trough and power tower solar technology cost and performance forecasts, 2003). Although a series of significant advancements in PTR have been introduced in recent years, the frequently failure of PTR is still major factor to limit the optimization and application of solar power technologies (Cheng et al., 2012; Qiu et al., 2016; Liu et al., 2010).

Large temperature gradient is the essential reason of inducing the thermal deformation and damage of PTR. Therefore, many researchers have adopted the method of heat transfer enhancement in absorber tube to decrease the temperature gradient: Mwesigye et al. (2014) had put forward that perforated plate can be inserted in tube receiver to decrease the temperature gradients of PTR for a parabolic trough solar collector, and the results of heat transfer performance analyses indicated that the thermal efficiency enhancement of PTR with perforated plate insert can reach up to 8% and the temperature gradient of tube receiver was decreased dramatically. In order to enhance the heat transfer performance and reduce heat exchanger size of solar parabolic trough system, Şahin et al. (2015) had proposed a concentric tube heat exchanger with different pitches of coiled wire turbulators and performed numerical simulations using a three dimensional CFD computer code to investigate the heat transfer and friction characteristics of the concentric tube heat exchanger. Their numerical results showed that the heat transfer enhancement by using turbulators can reach 228%. With the aim to increase the heat transfer performance and reliability of PTR, the symmetric/asymmetric outward convex corrugated tube designs were introduced for parabolic trough receivers by Wang et al. (2016a,b), and an optical-thermal-structural sequential coupled method was also developed to study the heat transfer performance and thermal strain of tube receiver for parabolic trough solar collector system. Their numerical results indicated that the maximum enhancement of overall heat transfer performance factor was 148% and the maximum restrain of von-Mises thermal strain was 26.8% by using symmetric/asymmetric outward convex corrugated tube as tube receiver for parabolic trough solar collector system. With the aim to increase the thermal efficiency of the commercial parabolic collector, a dimpled absorber tube with sine geometry had been researched by Bellos et al. (2016), the numerical simulation was conducted through Solidworks flow simulation studio and the numerical results indicated that the collector efficiency can be increased up to 4.25% by using nanofluids as heat transfer fluid.

In theory, most of the traditional heat transfer enhancement technologies are also suitable for PTRs (Song et al., 2014; Wang et al., 2013; Zheng, 2017): (i) decreasing thermal boundary layer, (ii) increasing flow interruption, (iii) increasing the velocity gradient of fluid near solid walls (Tao et al., 2002). Pin fin arrays inserting can decrease the thermal boundary layer and increase the flow interruption in the flow field, therefore it was widely adopted in industrial applications for heat transfer enhancement (Axtmann et al., 2016). In order to enhance the heat transfer rate in high speed multi-functional electronics, Chin et al. (2013) had experimentally and numerically investigated the usage of staggered perforated pin fins in these devices, and their results presented that the Nusselt number for the perforated pins was 45% higher than that for the conventional solid pin. With the aim to obtain the best thermal performance, Eren and Caliskan (2016) had experimentally researched the effects of inserting grooved pin-fins in a