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A numerical study of parabolic trough receiver with nonuniform heat flux and helical screw-tape inserts

Xingwang Song [a], Guobo Dong [b], Fangyuan Gao [b], Xungang Diao [a, b, *], Liqing Zheng [b, c], Fuyun Zhou [c]

[a] School of Energy and Power Engineering, Beihang University, Beijing 100191, China
[b] Solar Film Laboratory, School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
[c] CAMDA New Energy Equipment Co., Ltd, Dongguan, Guangdong 523407, China

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ABSTRACT

Effect of solar incidence angle was analyzed in order to accurately simulate the heat flux distribution around the absorber tube outer surface. Helical screw-tape inserts was proposed to homogenize the absorber tube temperature distribution and improve the thermal efficiency. Three dimensional periodical models of flow and heat transfer were established and solved with the heat flux of different transversal angle (β). The results show that β affects the flux distribution more greatly than longitudinal angle (φ). Transversal angle (β) of 11.567 mrad increases the relative change of heat loss (Q_{loss}) as inlet temperature rises, and also increases the maximum temperature on absorber tube ($T_{\max}$) and the maximum circumferential temperature difference (ΔT). But its effect reduces as Reynolds number rises. Within the range of studied *Re*, the helical screw-tape inserts of given geometrical parameters greatly reduce the Q_{loss}, $T_{\max}$ and ΔT, which indicates that helical screw-tape inserts is a feasible way to enhance the heat transfer inside the receiver.

1. Introduction

PTC (Parabolic trough collector) can be used on a large scale in solar thermal power generation [1,2], as well as in refrigeration [3] and seawater desalination [4]. In the PTC, solar radiation is reflected and concentrated on a linear receiver in focal line. HTF (Heat transfer fluid) flowing through the receiver absorbs the heat for further power generation or other industrial heating. The thermal performance of PTC and receiver has been widely researched by many scholars [5–10]. Most of the studies that probe into the theoretical calculations neglect the incidence angle of solar rays. Actually, the incidence angle determines the heat flux distribution on the absorber tube outer surface. Fig. 1 shows that the incidence angle (θ) can be decomposed into two components on two orthogonal planes: longitudinal angle (φ) and orientation angle error or transversal angle (β). In a collector with ideal concentration, solar incidence that lies in the longitudinal plane causes a circumferentially-nonuniform heat flux on the absorber tube. The nonuniform heat flux is normally treated as an important boundary condition of heat transfer in the receiver [11,12]. More accurate calculated results were obtained when the nonuniform heat flux rather than a uniform heat flux was taken into account [13,14]. The nonuniform heat flux also causes thermal stress in the absorber tube, leading to breaking risks of bellows [15,16] and limiting the achievable temperature of selective film that is coated on the tube external surface [17]. Wind or inherent error of control scheme [18] may cause an overall deflection of collector and consequently leaves the receiver into a defocus status where the heat flux is more nonuniform. EuroTrough consortium estimates that tracking error using today's shadow-band technology is about 2 mrad and that wind-induced tracking error is about 4 mrad given a 5 m/s average wind [19]. So both the temperature distribution and thermal performance of a receiver with unsatisfactory tracking may be worse than with ideal concentration, especially for a PTC with long-term operations. However, the influence of incidence that deviates from the longitudinal plane on heat transfer has not been reported.

Improvement of thermal performance and homogenization of temperature distribution on the absorber tube outer surface can be achieved simultaneously by heat transfer enhancement inside the tube. Many enhancement forms [20–25] have been put forward in the receivers, most of which are non-inserts and commonly used in

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* Corresponding author. Solar Film Laboratory, School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China. Tel./fax: +86 10 82313931.

E-mail address: diaoxg@buaa.edu.cn (X. Diao).

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Nomenclature

Symbols

A	surface area (m^2)
a	aperture width of collector (m)
C_p	isobaric specific heat capacity (J kg^{-1} K^{-1})
d_1	inner diameter of absorber tube (mm)
d_2	outer diameter of absorber tube (mm)
d_3	inner diameter of glass envelope (mm)
d_4	outer diameter of glass envelope (mm)
d_{core}	diameter of core-rod (mm)
EFF	thermal efficiency
F	focal length (m)
f	friction factor
g	gravity acceleration, m s^{-2}
H	diameter of screw-tape (mm)
h	average convective heat transfer coefficient (W m^{-2} K^{-1})
I_b	intensity of direct normal insolation (W m^{-2})
L	length of collector or receiver (m)
LHF	local heat flux (W m^{-2})
LCR	dimensionless local concentration ratio
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of photons
Nu	average Nusselt number
n	refractive index of glass
P	length of one twist (mm)
Q	heat (W)
Re	Reynolds number
T	temperature (K)
t	thickness of screw-tape (mm)
V	wind velocity (m s^{-1}); volume flow rate (L min^{-1})
Y	twist ratio

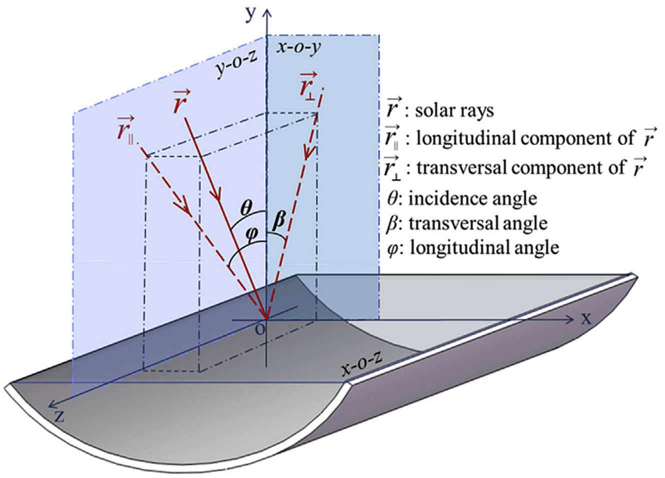
Greek symbols

α	absorptivity of selective coating
β	orientation angle error or transversal angle (Deg.)
γ	angle between surface normal and solar rays
ΔP_L	pressure loss per unit length (pa m^{-1})
ΔT	difference between T_{max} and T_{min} (K)
δT	difference between T_{max} of different β
ε	emissivity
θ	incidence angle (Deg.)
λ	thermal conductivity (W m^{-1} k^{-1})
μ	viscosity (pa $\times$ s)
ρ	reflectivity of parabolic trough; density (kg m^{-3})
τ	transmittance
φ	longitudinal angle

Subscripts

1	in the case of β of 0
5	in the case of β of 11.567 mrad
a	ambient; aperture
abs	absorbed heat
e	element on absorber tube surface
cal	calculated values
dp	dew point
g	glass envelope outside
in	inlet
loss	heat loss
max	maximum value
min	minimum value
o	outlet
ave	average
sky	sky
test	experimental results from literature
w	inner surface of absorber tube

heat exchangers. Service experiences of those non-inserts shows various drawbacks: impurities, great pressure loss and inconvenience for manufacture. For existing receivers, heat transfer enhancement via suitable inserts is favorable. Twisted tape is the most common inserts that enhances the heat transfer, and its performance in a receiver has been recently investigated [26]. Helical screw-tape is an improvement of the twisted tape and can be easily manufactured by coiling up annealed copper on a mandrel with a helical groove [27]. Comparing with twisted tape, helical screw-tape makes only part of in-tube fluid flow spirally by using less metal, and consequently avoids overmuch pressure loss [28]. More importantly, the screw-tape provides excellent performance at low Reynolds number (Re) and prevents the deposition of scaling [27].



o:an arbitrary point on the aperature.
z-axis: parallel to tracking axis; *y*-axis: perpendicular to the aperture plane.
x-o-z: aperture plane; *x-o-y*: transversal plane perpendicular to *z*-axis;
y-o-z: longitudinal plane perpendicular to *x-o-z* and *x-o-y*.

Fig. 1. Decomposition of incidence angle.

In this paper, the performance and temperature around the absorber tube outer surface were simulated and analyzed by considering various conditions including solar incidence angle and helical screw-tape inserts. First, the heat flux around the absorber tube was obtained applying MCRT (Monte Carlo ray tracing) method and was simplified. Then, the heat flux of different transversal angle (β) was used as heat input to periodical three-dimensional models. Flow and heat transfer in the receiver with/without inserts were simulated. Collector and receiver from CAMDA New Energy Equipment Co., Ltd were used (see Table 1 for parameters) in the models. Flow rates in the simulations were about 1 order below the regimes experienced in some practical applications, because the real flow rate in the CAMDA solar field that is small and lacks sufficient solar irradiance must be reduced to get high outlet temperature. Preliminary studies of the incidence angle and the inserts may provide a reference for receiver performance and for design of working conditions in solar field.

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