Energy 59 (2013) 666–675

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Nonuniform heat transfer model and performance of parabolic trough solar receiver

Jianfeng Lu [a,*], Jing Ding [a,*], Jianping Yang [b], Xiaoxi Yang [b]

[a] School of Engineering, Sun Yat-Sen University, Guangzhou 510006, China
[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of the Ministry of Education, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form
4 July 2013
Accepted 24 July 2013
Available online 16 August 2013

Keywords:
Parabolic trough
Solar receiver
Heat loss
Nonuniform heat transfer

ABSTRACT

The nonuniform heat transfer model and performance of parabolic trough solar receiver are theoretically investigated due to the energy balances between the heat transfer fluid, absorber tube, glass envelope and surroundings. The absorber tube and glass envelope are both divided into two regions for uneven solar radiation and wall temperature distribution, and then a nonuniform heat transfer model of solar receiver is established. According to the calculation results, the heat loss of solar receiver from the nonuniform model is a little higher than that from the uniform model, and the heat transfer inside the vacuum glass envelope is mainly dependent upon the radiation, while the convection and radiation both play important roles in the heat loss outside the glass envelope. Under offsun condition, the heat transfer of receiver is almost uniform with little differences of wall temperature and heat loss. Under onsun condition, the heat transfer of receiver is apparently nonuniform for higher wall temperature and heat loss in the positive region of glass envelope and absorber tube. As a conclusion, the heat transfer performances of parabolic trough solar receiver are better to be calculated by nonuniform model especially under onsun condition.

1. Introduction

Concentrated solar systems including parabolic trough collector, parabolic dish reflector and heliostat field collector [1] are widely used in many fields, and they are also research hot spots for clean and renewable energy. Solar parabolic trough collector is currently the prominent technology for solar thermal power plant [2–4], and it can also be widely used in air-conditioning and refrigeration [5], sea-water desalination [6], etc. The parabolic trough solar receiver mainly includes an absorber surrounded by a glass envelope and supported brackets. In order to increase the operating temperature and thermodynamic efficiency, the absorber is typically a stainless steel tube covered by selective coating with high absorptivity of solar radiation and low emissivity of infrared radiation, and the glass envelope with vacuum enclosure is used to reduce the heat loss.

The heat transfer performance of parabolic trough solar receiver is mainly affected by many factors such as receiver structure, absorber coating, wind. Dudley et al. [7] experimentally measured the heat loss and efficiency of solar parabolic trough collector under different conditions: vacuum envelope, air in envelope and bare tube, and found that the vacuum envelope can significantly reduce the heat loss. Ratzel et al. [8] analyzed the thermal conduction and natural convection heat losses in annular receiver. Naeeni and Yaghoubi [9] studied the heat transfer of wind flow around a parabolic collector, and found the flow field around the receiver was not symmetrical and it depended upon the wind boundary layer profile and collector orientation. Kennedy [10] reviewed the optical characteristics of solar selective coating materials in a wide temperature range. Clark [11] investigated the thermal and economical performances of parabolic trough receivers with the effects of design and manufacturing parameters. Govindaraj et al. [12] studied the performance of a solar parabolic trough collector with a thermal energy storage system.

Various prediction models have been proposed to analyze the heat loss and efficiency of solar parabolic trough collector in available literature. Edenburn [13] calculated the efficiency of a

* Corresponding authors. Tel./fax: +86 20 39332319.
E-mail addresses: lujfeng@mail.sysu.edu.cn (J. Lu), dingjing@mail.sysu.edu.cn (J. Ding).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.07.052

Nomenclature

C	radius ratio (−)
D	diameter (m)
F	transfer factor (−)
h	heat transfer coefficient (Wm^{-2} K^{-1})
I_s	direct solar irradiance (Wm^{-2})
K	incident angle modifier (−)
k	heat conductivity (Wm^{-1} K^{-1})
L	receiver length (m)
P	pressure (Pa)
Q	heat transfer (W)
q	heat flux (Wm^{-2})
R	radius (m)
T	temperature (K)
ΔT	the average absorber tube temperature above the surroundings (K)
u	velocity (ms^{-1})
W	collector width (m)

Greek symbols

α	absorptivity (−)
γ_c	intercept factor (−)
ε	emissivity (−)
ε_b	radiation heat flux of black body (Wm^{-2})
λ	mean free path (m)
ρ_c	collector reflectivity (−)
θ	angle (−)
ψ	collector end modifier (−)
τ	transmittance (−)
η	efficiency (−)
μ	viscosity (kgm^{-1} s^{-1})
σ	Stefen Boltzmann constant (Wm^{-2} K^{-4})

Subscripts

a	air
ab	absorption
c	convection, collector system
f	heat transfer fluid
g	glass envelope
loss	heat loss
non	nonuniform model
o	the opposite region
p	the positive region
r	radiation
s	surroundings
t	absorber tube
un	uniform model

cylindrical parabolic focusing collector by using an analytical heat transfer model for evacuated and nonevacuated cases. Dudley et al. [7] developed one dimensional steady state model based on thermal resistance analysis, and the model had a good agreement with the experimental data of SEGS LS-2 parabolic solar collector. Valladares and Velásquez [14] used a numerical model for single pass and double pass solar receiver. Padilla et al. [15] developed a heat transfer model for thermal analysis of parabolic trough solar receivers, and the mass and energy balances were applied in several segments of the receiver and envelope. Kalogirou [16] proposed a detailed thermal model of a parabolic trough collector receiver by EES (Engineering Equation Solver). In general, most prediction models and correlations assumed that the solar flux and wall temperature of parabolic trough solar receiver were uniform.

In practice, the heat transfer performances of parabolic trough solar receiver can be nonuniform because of the uneven solar flux on the absorber. Jeter [17,18] studied the nonuniform distribution of concentrated solar radiation in parabolic collectors by a semi-finite analytical formulation. Lu et al. [19] analyzed the heat transfer characteristics of an external receiver pipe under unilateral concentrated solar radiation. He et al. [20] and Chang et al. [21] proposed a coupled simulation method based on MCRT (Monte Carlo Ray Trace) and FVM (finite volume method) to simulate the heat transfer of parabolic trough solar collector, and considered the effects of nonuniform solar energy flux. Besides, Eck et al. [22] studied a two-dimensional plane stress model by considering the local nonuniform solar heat distribution on absorber.

The objective of this article is to investigate the nonuniform heat transfer and absorption characteristics of parabolic trough solar receiver under uneven solar radiation. The basic physical models of solar energy flux, nonuniform radiation and heat convection are proposed to investigate parabolic trough solar receiver. The heat loss and efficiency of solar receiver are further analyzed and compared by uniform model, nonuniform model and experimental data. Additionally, the nonuniform wall temperature and heat loss distributions of solar receiver are reported under onsun and offsun conditions.

2. Nonuniform heat transfer model of parabolic trough solar receiver

2.1. General description

The heat transfer of parabolic trough solar receiver has been widely investigated by considering the effects of collector structure, absorber coating, natural convection, etc. Till now, available calculation results are mostly based on the uniform assumptions of solar flux and wall temperature, while the nonuniform heat transfer performances of solar receiver need to be further studied. Fig. 1a presents the concentrated solar radiation phenomena on solar receiver in Energy Conservation Center, and the solar radiation distribution is very uneven. Fig. 1b describes the distribution of concentrated ratio in solar receiver [17,18], and concentrated solar radiation mainly distributes in the positive region face to collector, while it sharply decreases in the opposite region back to collector. According to Fig. 1, the uniform solar flux model can be quite different from the radiation distribution under certain conditions, and the nonuniform model with uniform solar flux only on the positive region face to the collector will be proposed in the present article. Compared with the practical solar receiver, the uniform model can describe the integral heat transfer performance, while the nonuniform model can analyze the nonuniform temperature and heat transfer. In addition, the nonuniform temperature distribution can directly affect the structure of tube and glass envelope for thermal stress.

The heat transfer model of parabolic trough solar receiver is based on the energy balances between the heat transfer fluid, absorber tube, glass envelope and surroundings. Fig. 2 presents the heat transfer and thermal resistance models of parabolic trough solar receiver. Because of uneven solar flux, the absorber tube is divided into two regions: the positive region face to the collector, and the opposite region. Meanwhile, the glass envelope is also divided into two regions with different temperature and solar flux: the positive region face to the collector, and the opposite region. In addition, the sky and collector surface are considered as the