International Journal of Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Multi-scale numerical analysis of flow and heat transfer for a parabolic trough collector

Zhen Tang, Xin-Peng Zhao, Zeng-Yao Li, Wen-Quan Tao *

Key Lab of Thermo-Fluid Science and Engineering of MOE, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 25 June 2016
Received in revised form 1 September 2016
Accepted 1 September 2016
Available online xxxx

Keywords:
Parabolic trough collector
DSMC
Coupled heat transfer
Multi-scale

ABSTRACT

This paper numerically investigated the coupled flow and heat transfer of a parabolic trough collector (PTC), with the non-uniform heat flux boundary condition on the absorber wall and the rarefied gas effects in the annular vacuum gap being taken into consideration. A fully coupled cross-sectional heat transfer model is established with Direct Simulation Monte Carlo (DSMC) method for the rarefied gas flow and heat transfer in the vacuum annual gap. The PTC tube efficiency can be obtained from the above simulation for a given HTF temperature. Such simulation is conducted for several specified HTF temperature and different efficiency data are obtained. These data are fitted by an equation. This equation is then used to advance the HTF temperature in the axial direction. In such a way a simplified 3D model for the design of a PTC receiver is obtained. Cross-sectional simulation results show that when the gas pressure is less than 0.1 Pa further decrease in pressure makes no further contribution to reduce the heat loss. The effects of periphery non-uniform distribution of heat flux, coating material emissivity, envelope diameter and HTF inlet velocity on the PTC efficiency are discussed. An operation variant is proposed by using the 3D model by which the total PTC tube length can be reduced for a given thermal load.

1. Introduction

Parabolic trough collector (PTC) is one kind of solar receivers which are the energy conversion devices by converting solar radiant energy of sunlight focused by the mirrors to thermal energy [1–3]. This solar receiver consists of a stainless absorbing tube and a surrounding annular vacuum space with a glass envelope. The stainless tube, with a selective emissivity coating on the surface, absorbs the radiant energy transmitting through the glass tube, converts it to thermal energy and transfers the thermal energy to the heat transfer fluid (HTF) flowing within the tube. The heated HTF flows to a heat accumulator and stores heat in it. After that, the stored heat is used to produce high temperature steam in a steam generator, which would drive a conventional turbine-generator to produce electricity. Now the efficiencies of the steam generator (about 98%), steam turbine (about 88%) and electric generator (about 95%) are quite high and stable because the input conditions of these machines are fixed by adopting the heat accumulator. But the efficiency of PTC is not high (about 36%) and changes a lot because of the effects of various factors [4] shown in Fig. 1. At the present time the whole solar system efficiency is still at a low level (about 30%) [5], mainly because the PTC's efficiency is low. So increasing the PTC's efficiency plays an important role in making the solar electricity generation system being more compatible with fuel-power plant.

In order to gain a high efficiency of the PTC, the manufacturers adopt some advanced techniques to reduce heat loss from the absorber tube to the environment, such as using a low thermal emittance cermet selective coatings on the absorber and adopting a vacuum annular glass envelope surrounding the absorber tube. Usually, the annular gap between the absorber tube and the glass envelope is kept at a high vacuum. The selective coatings have the characteristics of high absorptivity ($\alpha = 0.98$) and low emittance ($\varepsilon \leqslant 0.15$) which will reduce the self-thermal radiation of the absorber. The convection heat transfer in the gap is mainly affected by the gas pressure in the gap [6]. Usually the pressure is designed to be lower than 0.001 Pa. On the other hand, the absorber tubes are heated by non-uniform heat flux resulted from the concentration of the parabolic trough [2], which leads to the non-uniform distribution temperature of the tube. So the emittance selective coatings of cermet, the gas pressure in the annular gap and the non-uniform heat flux on the tube are the major factors affecting the efficiency of the PTC [7,8]. Apart from the above-mentioned three factors, the inlet temperature and volume flow rate of HTF, solar radiation, ambient air temperature, and

* Corresponding author.
E-mail address: wqtao@mail.xjtu.edu.cn (W.-Q. Tao).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.002
0017-9310/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

D	diameter (m)	t	time (s)
E	energy (J)	k	thermal conductivity (W/(m·K))
c_p	heat capacity (kJ/(kg·K))	V	velocity (m/s)
q	heat flux (W/m)		
h	heat transfer coefficient (W/(m^2·K))	*Greek symbols*	
Kn	Knudsen number	δ	absorber tube thickness (m)
d_{mol}	molecule diameter (m)	α	absorptivity
Nu	Nusselt number	κ	Boltzmann constant
P	pressure (Pa)	ρ	density (kg/m^3)
Pr	Prandtl number	ε	emittance
Re	Reynolds number	ν	kinematic viscosity (mm^2/s)
T	temperature (K)	$\bar{\lambda}$	mean free path (m)

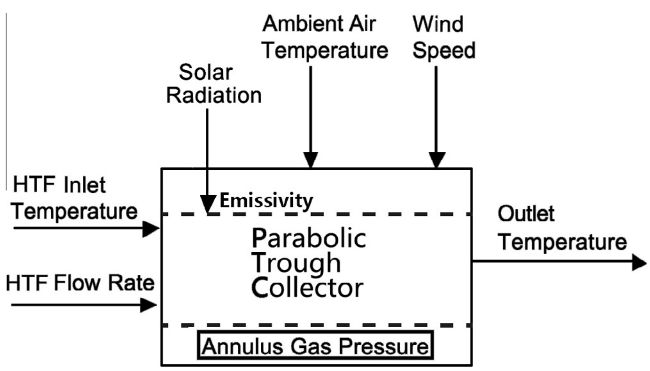

Fig. 1. Black box model of the heat collector element.

wind speed have their affections on the efficiency of a PTC as well, as shown in Fig. 1. While the outlet temperature of the HTF is the production of a PTC.

In order to investigate the effects of the above factors numerical simulation and experimental measurement have been widely conducted. The results of experimental studies are often expressed by correlation or fitting formulas. In this regard, the investigation conducted in [6] is quite representative, and is introduced a bit in detail below. The following assumptions are made in the paper: (1) for the temperature difference to determine the convection heat transfer between the HTF and the absorber wall, the HTF temperature is the fluid bulk temperature; (2) the flow is laminar with a uniform flux; (3) for the convection heat transfer between the absorber tube and glass envelope, the convection heat transfer coefficient is constant and the temperatures of the absorber tube and glass are kept at different but uniform (The author specifically remind that "At low pressures (<0.0001 torr), the heat transfer may be slightly overestimated."); (4) for the convection heat transfer between the glass envelope and the atmosphere, a long isothermal horizontal cylinder is assumed. A fitting formulas of performance analysis based on the first law of thermodynamics is used in [6] to study all these factors. The heat transfer analysis of a PTC is implemented by the Engineering Equation Solver. Such studies could provide some necessary information for a quick engineering estimation, but could not obtain details of the transfer process which are necessary for further improving the efficiency of a PTC.

A number of studies for which the CFD method were used focus on the inlet temperature and volume flow rate of HTF [9,10]. In [9], a three-dimensional simulation based on finite element method of a PTC using molten salt as HTF was conducted. But the authors did not simulate the flow and heat transfer in the annulus. In [10], the authors analyzed the effect of the utilization of internal finned tubes with computational fluid dynamics. Results showed an improvement potential in parabolic trough solar plant efficiency by the application of internal finned tubes.

For the solar radiation, a coupled simulation method based on Monte Carlo Ray Trace (MCRT) and finite volume method (FVM) is established to solve the coupled heat transfer problem of radiation, heat conduction and convection in the PTC in [11,12]. The numerical results, especially the heat flux distributions along the periphery of the glass tube , were in good agreement with experimental data of LS2 PTC of Sandia National Laboratory [13], proving that the model and method proposed in [2] is feasible and reliable. In [14] a detailed one dimensional view factors for a short annulus is presented for the radiative heat transfer.

For the annulus gas pressure, some simulations by the direct simulation of Monte Carlo (DSMC) model used uniform wall temperature boundary [15,16]. A unified two-dimensional numerical model was used for the coupled heat transfer process in a PTC and the effects of tube diameter ratio were numerically analyzed [17]. Considering the very non-uniform heat flux distribution along the tube periphery, helical screw-tape inserts was proposed to homogenize the absorber tube temperature distribution and improve the working condition of the PTC tube [18]. In [19], DSMC was used to analyze the conduction heat loss from a PTC with controlled pressure within the annular gap. For the effects of ambient air temperature and wind speed, numerical simulations for the outside convective heat transfer were used in [20–23]. FVM was used to solve the governing equations and the SIMPLE algorithm was employed to deal with the coupling between velocity and pressure in [22,23]. A numerical study based on Large Eddy Simulations was carried out to characterize the wind loads and heat transfer coefficients [22,23]. In reality, the heat transferred by rarefied gas in the annular gap is coupled with both the heat transfer in the absorber tube and that outside the glass envelope.

Most these works used the uniform or constant solar flux assumption along the tube periphery and many correlations based on a uniform or constant temperature assumption, thus making the simulation of the entire heat transfer processes being not fully coupled. The aim of this paper is to provide a complete coupled heat transfer model, from heat transfer of HTF within the inner tube to the heat transfer from envelope to the atmosphere to study the affecting factors of PTC, with major focus being put on the influence of the non-uniform heat flux and rarefied gas heat transfer in the annual gap by DSMC. In the following presentation the physical model and numerical method will be briefly introduced, then numerically simulated results will be provided in details, including cross-sectional parameter distributions and axial-wise

Please cite this article in press as: Z. Tang et al., Multi-scale numerical analysis of flow and heat transfer for a parabolic trough collector, Int. J. Heat Mass Transfer (2016), http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.002