Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Thermal analysis of solar central receiver tube with porous inserts and non-uniform heat flux ☆

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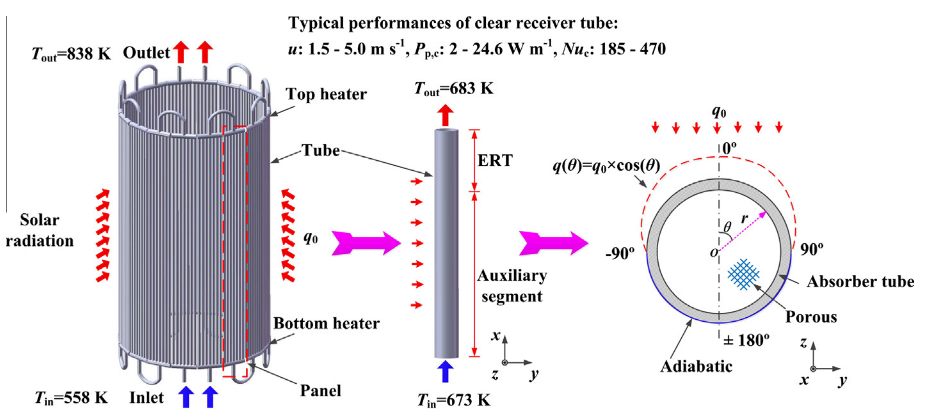
HIGHLIGHTS

- A solar central receiver tube with non-uniform heat flux is numerically studied.
- A new method is suggested to determine the configurations of porous inserts.
- Effects of porous insert layouts on the performance of receiver tube are analyzed.
- Some optimal porous insert configurations are proposed for different purposes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form 16 November 2015
Accepted 29 November 2015
Available online xxxx

Keywords:
Solar energy utilization
Central receiver tube
Heat transfer enhancement
Porous medium
Numerical simulation
Optimization

ABSTRACT

In this paper, enhancement for convection heat transfer of turbulent flow in a solar central receiver tube with porous medium and non-uniform circumferential heat flux was numerically investigated. A new method was introduced to build different porous medium configurations in a unified grid system. Four kinds of enhanced receiver tubes (ERTs) with different porous insert configurations were modeled to optimize the performance of ERT. Furthermore, parameters including filling ratio of porous medium, thermal conductivity ratio (thermal conductivity of porous medium versus that of working fluid), porosity and Reynolds number were analyzed. The results showed that ERT partially filled with porous medium has better heat transfer performance than that fully filled with porous medium. The configuration of porous insert for optimal thermal or thermo-hydraulic performance is interactively affected by all the parameters discussed in this paper. The thermal conductivity ratio is the most crucial parameter to the thermal or thermo-hydraulic performance of ERT. The value of thermal conductivity ratio should be greater than 100 to obtain a good thermo-hydraulic performance. The ERTs with horizontal cylindrical segment shaped porous inserts and hollow cylinder shaped porous inserts are proposed because they can obtain optimal thermal or thermo-hydraulic performance.

1. Introduction

Solar power tower (SPT), as a primal concentrating solar power (CSP) technology, has numerous remarkable advantages including low average cost and large-scale power generation [1,2]. In SPT

☆ This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28–31, 2015, Abu Dhabi, UAE (Original paper title: "Optimization of Porous Insert Configuration in a central Receiver Tube for Heat Transfer Enhancement" and Paper No.: 514).

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http://dx.doi.org/10.1016/j.apenergy.2015.11.039
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Nomenclature

A	flow area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
D_i	inner diameter of receiver tube (m)
f	friction factor
F	inertia coefficient
h	heat transfer coefficient (W m^{-2} K^{-1})
h'	height of catalyst (m)
H	dimensionless height of porous medium
K	permeability (m^2)
L	length of ERT (m)
L_a	length of auxiliary segment (m)
Nu	Nusselt number
p	pressure (Pa)
q	heat transfer rate per unit area (W m^{-2})
q_0	heat flux at tube crown (W m^{-2})
Re	Reynolds number
T	temperature (K)
u, v, w	superficial velocity at x, y, z direction respectively (m s^{-1})
U	dimensionless x velocity component
x, y, z	Cartesian coordinates (m)

Greek symbols

α	binary flag
ε	turbulent energy dissipation rate (m^2 s^{-3})
θ	circle angle (deg)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	kinetic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	density (kg m^{-3})
σ	turbulent Prandtl number
φ	porosity

subscripts

c	clear receiver tube
e	effective
f	fluid
in	inlet
m	mean
out	outlet
por	porous medium
s	solid
w	wall

system, the receiver is a key component because it converts the solar radiation concentrated by heliostat field into thermal energy. Nevertheless, the typical optical concentration factor of SPT can reach as high as 1000 and the corresponding solar flux impinging on the receiver can reach up to 1.0 MW m^{-2} [3]. Meanwhile, the distribution of solar flux on the receiver is significant non-uniform. These extreme working conditions make the most uncertain lifetime of receiver [4]. Therefore, many studies have focused on predicting and improving the performance of receiver for SPT [5,6].

Being a typical receiver for SPT, tubular receiver is applicable to various heat transfer fluid (HTF), such as supercritical carbon dioxide, synthetic oils, liquid sodium, water/steam and molten salt [7,8]. The tubular receiver consists of many paralleled tubes. The high flux density and non-uniform flux distributing on each receiver tube can cause high temperature gradients within receiver tube wall and flow region, which has been proven by theoretical, numerical and experimental methods [9–17]. The uneven temperature field may result in many problems [18–22] such as aggravating the plastic deformation of receiver tube, facilitating degradation of the selective absorptive coating and the heat transfer fluid (e.g. thermal oil and molten salt) and decreasing the allowable solar flux density of system. Heat transfer enhancement can be employed to solve these problems due to its ability to decrease the irreversibility of heat convection [23,24].

Some methods of heat transfer enhancement have been put forward for the solar receiver tube with non-uniform heat flux. He et al. [25] proposed unilateral longitudinal vortex generators to enhance heat transfer in a parabolic trough receiver tube. The longitudinal vortex generators were only stamped on the side of the receiver tube with high heat flux. The results showed that the comprehensive heat transfer performance is improved. Muñoz et al. [26] numerically analyzed the thermal, mechanical and hydrodynamic performance of internal helically finned tube for parabolic trough, and found that using the enhanced tube can reduce the temperature gradients within the tube wall and increase the efficiency of solar plant. However, it is difficult to manufacture the special receiver tube mentioned above. Inserting porous medium is another effective way to enhance convection heat transfer in the receiver tube by rebuilding the velocity field and increasing the effective thermal conductivity of fluid. More importantly, the porous can be easily inserted into the receiver tube by gluing with thermal epoxy, soldering, joining, etc. [27,28]. Therefore, the applications of porous inserts to enhance heat transfer of the receiver tube were extremely extensive. Reddy et al. [29–31] numerically investigated the heat transfer enhancement of parabolic trough receiver tubes with porous disc and porous block. The effects of porous disc/block configurations on the heat transfer performance of receiver tube with non-uniform heat flux were studied. Ghasemi et al. [32,33] proposed porous segmental rings for heat transfer enhancement of parabolic trough receiver tube. The effects of segmental rings layouts on the heat transfer and system performance for non-uniform heat flux were discussed. Mwesigye et al. [34] studied the thermal and thermodynamic performance of a parabolic trough receiver tube with porous inserts. The porous medium was centrally placed in the receiver tube to avoid any possible hot-spots caused by non-uniform heat flux distribution. Wang et al. [28] numerically analyzed the enhancement of forced convective heat transfer in a parabolic trough receiver tube with metal foams and non-uniform heat flux. Horizontal cylindrical segment shaped porous inserts were proposed to obtain the optimal thermal or thermo-hydraulic performance. Based on the studies above, it can be found that the non-uniform heat flux is an important factor when the heat transfer enhancement for the receiver tube is studied. However, most heat transfer enhancement methods of receiver tube with non-uniform heat flux were proposed for solar parabolic trough system. For central receiver tube, more studies are needed to find out the appropriate heat transfer enhancement, since the heat flux distribution of central receiver tube is different from that of parabolic trough receiver tube.

In this paper, the heat transfer enhancement in a solar central receiver tube with porous medium and non-uniform heat flux was numerically investigated. A new method was adopted to determine the different porous medium configurations in a unified grid system. Based on this new method, the porous insert configurations were optimized for improving thermal or thermo-hydraulic