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Numerical study of heat transfer enhancement in the receiver tube of direct steam generation with parabolic trough by inserting metal foams

P. Wang [a,b,*], D.Y. Liu [a], C. Xu [c]

[a] College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China
[b] College of Bourns, Department of Mechanical Engineering, University of California, Riverside, CA, USA
[c] College of Energy and Electricity, Hohai University, Nanjing, China

HIGHLIGHTS

- ▶ Optimum thermo-hydraulic performance is obtained when $H = 0.25$ (bottom).
- ▶ Optimum thermal performance is obtained when $H = 0.75$ (top).
- ▶ Maximum circumferential temperature difference decreases about 45%.
- ▶ Layout, H effects on the thermal performance greatly, but φ effects on it slightly.
- ▶ Main methods and results can be extended to all solar concentrated receiver tube.

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ABSTRACT

The present numerical simulation investigates the effect of inserting metal foams in receiver tube of parabolic trough collector on heat transfer. The effects of layout (top/bottom), geometrical parameter (H), and porosity (φ) of metal foams on the flow resistant, heat transfer and thermo-hydraulic performance are analyzed. Optimum thermo-hydraulic performance considering the flow resistance increase is obtained when $H = 0.25$ (bottom), Nu increases about 5–10 times with the increase of f 10–20 times and the PEC range from 1.4 to 3.2. Optimum thermal performance is obtained when $H = 0.75$ (top), Nu increases about 10–12 times with the increase of f 400–700 times and the PEC range from 1.1 to 1.5. The maximum circumferential temperature difference on the out surface of receiver tube decreases about 45% which will greatly reduce the thermal stress. The result shows that for constant layout and φ, the H effects on the thermal performance greatly, but for constant layout and H, the φ effects on the thermal performance slightly. Moreover, the layout in view of no-uniform heat flux boundary affects the heat transfer significantly. These methods and results can be extended to the heat transfer enhancement of all the solar concentrated receivers.

1. Introduction

Solar thermal plant based on parabolic trough collector (PTC) is the most successful solar technology demonstrated by SEGS plants in California. Direct steam generation in the receiver tube, so called DSG process can significantly reduce the cost of electricity produced by plant with a higher efficiency [1]. Thermal performance of the receiver tube in PTC influences the system efficiency significantly. Almanza [2,3] investigated the receiver behavior of DSG process with parabolic trough under low operating parameters. Bending occurred due to the high circumferential temperature difference of receiver tube, a compound tube was proposed to deal with this problem. Odeh [4,5] carried out the performance analysis of solar parabolic trough collector with synthetic oil and water as working fluids. Eck [6,7] conducted the DISS project to investigate the effect of irradiation, mass flux, operating pressure on the circumferential temperature difference of receiver tube.

In recent years, the application of porous media on enhancing heat transfer is extensive, the mechanism can be concluded as follows: (1) disturb the boundary layer to decrease the thermal resistance; (2) increase the intensity of turbulence to augment mixing of fluid; and (3) increase the effective thermal conductivity of fluid due to the high area density and thermal conductivity of porous media. Hwang and Chao [8] carried out heat transfer measurement in sintered porous channels for different diameter ratio, heat flux

* Corresponding author at: College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China. Tel.: +86 025 83786175, +86 13851884286.

E-mail address: Franciswp2012@163.com (P. Wang).

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Nomenclature

b	half-thickness of metal foams bump
C_p	specific heat of steam at constant pressure
D_g	diameter of cover glass tube
D_i/D_o	inner/outer diameter of absorber tube
f	friction factor
f'	focal length
F	inertia coefficient
G_k	production of turbulent viscosity
h	local convective heat transfer coefficient
h'	height of metal foams
H	dimensionless height of metal foams
H'	height of metal foams in [9]
I	direct normal solar irradiance
k	kinetic energy
K	permeability
l	length of porous media
l'	length of parabolic trough
L'	length of porous media in [9]
L	half-length of metal foams fiber
N_c	number of nodes in circumferential direction
N_a	number of nodes in axial direction
Nu_l	local Nusselt number
Nu_r	dimensionless Nusselt number
p	pressure
Pr	Prandtl number
PEC	performance evaluation criteria
q	heat flux
Q_m	mass flux of steam
r	area ratio
Re	Reynolds number
S	source term
T	temperature
u_i	Darcian velocity at x, y, z direction respectively
$\vec{u}$	velocity vector
W'	width of metal foams in [9]
Wa'	aperture of parabolic trough

Greek symbols

α'	absorptance
ε	turbulent dissipation rate
ε'	emittance
φ	porosity
λ	thermal conductivity
μ	dynamic viscosity
μ_t	turbulent viscosity
θ'	rim angle
θ	circle angle
ρ	density
ρ'	reflectance
σ_T	turbulent Prandtl number
σ_k	turbulent Prandtl number for didiffusion of k
σ_ε	turbulent Prandtl number for didiffusion of ε
τ'	transmittance
υ	kinetic viscosity

subscripts

a	average
c	clear tube
e	effective
f	fluid
g	glass tube
in	inlet
m	mean value
s	solid matrix of metal foams
w	wall

and Reynolds number. Calmidi and Mahajan [9–11] carried out the experimental and numerical study on the heat transfer characteristic of metal foams. Zhao [12] used numerical method to analyze the fluid flow and heat transfer in the metal foams filled tube-in-tube heat exchanger, predicted the optimum parameters of inserted metal foams. Nimr and Alkam [13,14] carried out the two-dimensional numerical study of the flat and tubular solar collectors partially filled with porous media substrates at a laminar flow state. Sopian [15] experimentally investigated the characteristics of a double-pass solar collector filled with porous media. Kumar [16] analyzed the thermal performance of parabolic trough collector joining with semicircular porous disk with VP1 oil as working fluid. Pavel and Mohamad [17] analyzed the fluid flow and heat transfer in the pipe partially filled with porous media at laminar flow state experimentally. Numerical simulation result compared with experiment shows that the properties of porous media influent the numerical result significantly, so it needs to be determined by experiment. Huang and Liu [18] proposed the conception of core flow heat transfer enhancement; conducted experimental and numerical studies on the tube filled with porous media range from laminar state to turbulent state, the effect of inserting porous media at fully developed turbulence region is weaker relatively compared to that at laminar flow region.

Numerous heat transfer studies have been carried out in tube or rectangular channel but there is no article focus on the heat transfer enhancement in the receiver tube of parabolic trough collector partially filled with high porosity metal foams. So in this paper three-dimensional numerical simulation on the receiver tube of parabolic trough collector by inserting metal foams is performed. Realistic non-uniform heat flux boundary and the experimentally measured physical properties of three different metal foams are employed to accurately describe the heat transfer characteristic in superheated section of DSG system. The effects of layout (top/bottom), geometrical parameter, and porosity of metal foams on the fluid flow and heat transfer are analyzed. The thermal performance of the receiver tube has been analyzed to obtain the optimum parameters of inserted metal foams.

2. Model description

2.1. Physical problem and assumption

The parabolic trough collectors (PTCs) of DISS project are chosen as the physical model in order to compare the simulation result with the experimental data. Fig. 1a and b. schematically shows the LS-3 PTC in DISS project and the cross section of receiver tube respectively. Detailed parameters [19] of the PTC are shown in Table 1. The concentrated solar radiation is transferred by the superheated steam flowing through the receiver tube partially or fully filled with metal foams material.

In the present study, two series (see Table 2) of metal foams with different geometric parameters and physical properties are installed in the receiver tube. The geometrical parameters of the inserted metal foams can be defined by the dimensionless height $H = h'/D_i$ (see Fig. 1b). The metal foams will be processed to the desired shape by wire cut electrical discharge machining (WEDM) firstly, and then to be installed in the tube by soldering [20].