Applied Energy 112 (2013) 1367–1375

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Study on flow and heat transfer characteristics of composite porous material and its performance analysis by FSP and EDEP

Zhi-Qiang Yu, Yong-Liang Feng, Wen-Jing Zhou, Yu Jin, Ming-Jie Li, Zeng-Yao Li, Wen-Quan Tao *

Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

HIGHLIGHTS

- ▶ The turbulent flow and heat transfer for four porous materials are studied.
- ▶ The field synergy principle and entransy dissipation extremum principle are used.
- ▶ The consistency of the above two principles is demonstrated.
- ▶ The values of Nu at given T_w are larger than that of given q_w for the cases studied.

ARTICLE INFO

Article history:
Received 26 September 2012
Received in revised form 8 February 2013
Accepted 19 February 2013
Available online 3 May 2013

Keywords:
Air receiver
Composite porous material
Flow and heat transfer performance
Field synergy principle
Entransy dissipation extremum principle

ABSTRACT

In this paper, the heat transfer characteristics of porous material adopted in the receiver of a concentrated solar power (CSP) with different structure parameters are numerically investigated. The commercial software FLUENT and the user defined function program (UDF) are adopted to implement the simulation. The porous material geometry is represented by periodic structures formed with packed tetrakaidecahedron. The air flow and heat transfer characteristics under the boundary conditions of constant heat flux and constant wall temperature are studied. The field synergy principle (FSP) and the entransy dissipation extremum principle (EDEP) are used to analyze the flow and heat transfer performance of the composite porous material. From the numerical results the best composite of the porous material is obtained. The effects of different boundary conditions are revealed. It is also demonstrated that the FSP and the EDEP are inherently consistent.

1. Introduction

The 21st century is the time when the science and technology are developing rapidly and the energy crisis and the environment pollution problems have been turning into the most important affairs. All countries pay their attentions to the new energy, like the wind energy, the solar energy, the water energy, the geothermic energy, and the tide energy. In the solar power generation, the main research region is the tower solar thermal power generation. In the tower power generation system, the key equipment of heat transfer is the receiver which receives the solar energy and transmits it to the heat transfer medium. In recent years, researchers have developed many highly efficient solar receivers [1–4]. Fig. 1 is the diagram of a tower concentrated solar power (CSP) system. The heat transfer medium in the tower solar receiver is air [5–8]. Fig. 2 is the diagram of the pressurized volumetric air receivers [3]. From Fig. 2 we can find that the main heat transfer component in the air receiver is the porous material (i.e., the inlet/outlet absorber in Fig. 2). The porous material has many unique advantages, such as large surface area, low density, light weight, sound insulation, and good penetrability, hence, is widely adopted as the intermedium of absorbing solar energy [9–12].

During the working process of the air receiver, the heliostat field focuses the solar light to shoot on the interior of the air receiver and the solar energy irradiates the porous material. Then the porous material absorbs the solar energy and is heated. In the receiver, when the air flows from outside through the porous material it is heated, then the heated air flows out the receiver to produce water vapor.

In the theoretical and numerical researches, the porous material structure is often simplified to ideal configuration, like a series of periodical cylinder, club, and cube [13–16]. The more complicated research models are the cube model (Dul'nev model), face center model, volume center model, Weaire–Phelan unit model, Kelvin tetrakaidecahedron model and so on [17–19]. Wu et al. [20] used the tetrakaidecahedron model and FLUENT software to predict

---

* Corresponding author. Tel./fax: +86 29 82669106.
E-mail address: wqtao@mail.xjtu.edu.cn (W.-Q. Tao).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.02.054

Nomenclature

d	mean cell size of the tetrakaidecahedron unit (mm)
L_s	length of column framework in tetrakaidecahedron unit (mm)
d_s	diameter of column framework in tetrakaidecahedron unit (mm)
ε	porosity
ρ	fluid density (kg m$^{-3)}$
c_p	specific heat of the fluid (J kg^{-1} K^{-1})
u	fluid velocity in the x direction (m s^{-1})
v	fluid velocity in the y direction (m s^{-1})
T	temperature (K)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
β	angle of the field synergy (°)
$\overline{U}$	dimensionless velocity
$\overline{T}$	dimensionless temperature
$\bar{y}$	dimensionless coordinate y
ΔE	entransy dissipation (W K)
Q	heat transfer rate (W)
ΔT_m	temperature difference of heat transfer (K)
s	surface area of the porous material (m^2)
V	volume of heat transfer (m^3)
A	area (m^2)
h	heat transfer coefficient (W m^{-2} K^{-1})
l	characteristic length (mm)
m	mass flux (kg)
Δe	entransy flux dissipation (W K m^{-2})
q	heat flux (W m^{-2})
R	thermal resistance of heat transfer (K m^2 W^{-1})
η	fluid dynamic viscosity (kg m^{-1} s^{-1})
λ	fluid thermal conductivity (W m^{-1} K^{-1}) coefficient
ν	fluid kinematic viscosity (m^2 s^{-1})

Subscript

s	solid
w	solid wall
x	coordinate x
∞	far-field region
t	thermal boundary layer
h	heat
m	mean value
a	air
tr	heat transfer
in	inlet
i	certain point of the calculation region
p	per
E	entransy

the convection heat transfer coefficient between the air and porous foam ceramic. From the calculation results, the relationships between the porosity, air velocity, unit size, temperature and the convection heat transfer coefficient were obtained. Petrasch et al. [21,22] used computed tomography (CT) method to get the true net characteristics of porous foam and numerically simulated the penetrability and interface heat transfer performance. The tetrakaidecahedron model can present the major structure characteristics of the usual porous material quite well, and can be adequately numerically simulated. So the tetrakaidecahedron model is used in this paper for the porous material study.

As indicated above the porous material has an advantage of large ratio of surface area over volume, which is an important way for enhancing heat transfer. In the study of enhancement mechanism of convective heat transfer, researchers have made big progress. Guo et al. [23–25] revealed the physical mechanism of single phase convection heat transfer and presented the field synergy principle (FSP) between velocity and temperature gradient field. According to the FSP, the intensity of fluid convective heat transfer is not only affected by the velocity and temperature gradient, but also is influenced by the synergy degree between the velocity vector and fluid temperature gradient [26]. The FSP is tested and verified via a lot of numerical calculations and experiments [27–32]. It can unify all existing mechanisms for enhancing single phase convective heat transfer [28]. The FSP can provide a guidance for the study of enhancing convective heat transfer.

There are two irreversible processes in the convection heat transfer: momentum transfer and heat transfer. The irreversibility of the momentum transfer leads to the viscosity dissipation, and then the irreversibility of the heat transfer would bring some kind of dissipation. From the irreversibility of the thermodynamics, Bejan [33,34] suggested that the entropy generation is used to evaluate the irreversible performance of convection heat transfer. He pointed out that the minimum total entropy generation can be used to optimize convection heat transfer process. This is called the thermodynamic optimization. It is well-known that the entropy and entropy generation are the physical quantities that indicate the ability of transforming thermal energy to work. The minimum entropy generation is the object function of optimization which can be applied for energy conversion—from thermal energy to work.

To explore the object function of optimizing heat transfer process, Guo et al. [35] presented a new physical quantity—entransy. Its physical meaning is the ability of a body to transfer its internal energy (heat) to the environment. In the heat transfer process, the

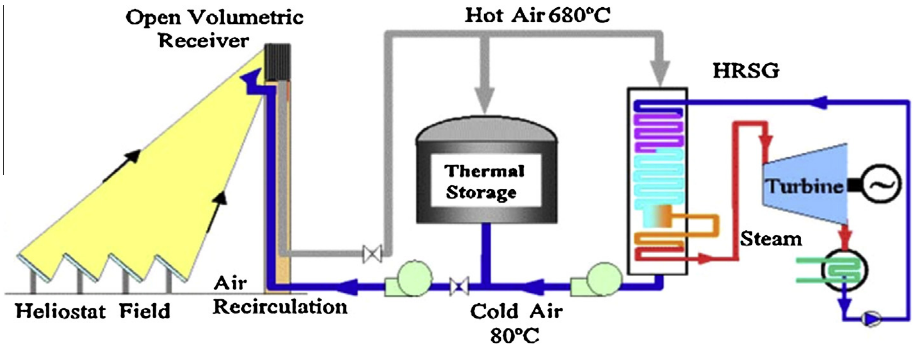

Fig. 1. Tower CSP system diagram.