Renewable Energy 74 (2015) 448–455

Contents lists available at ScienceDirect

Renewable Energy

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

Convection–radiation heat transfer in solar heat exchangers filled with a porous medium: Homotopy perturbation method versus numerical analysis

Maziar Dehghan [a,*], Yousef Rahmani [b,c], Davood Domiri Ganji [b], Seyfollah Saedodin [a], Mohammad Sadegh Valipour [a], Saman Rashidi [a]

[a] Mech. Eng. Dep., Semnan University, 35196-45399 Semnan, Iran
[b] Mech. Eng. Dep., Babol Noshirvani University of Technology, 4714871167 Babol, Iran
[c] Iranian Central Oil Field Company, NIOC, 1585653745 Tehran, Iran

ARTICLE INFO

Article history:
Received 28 May 2014
Accepted 16 August 2014
Available online 7 September 2014

Keywords:
Radiation–convection
Heat exchanger
Solar thermal usage
Cellular porous medium
Homotopy perturbation method

ABSTRACT

The case of combined conduction–convection–radiation heat transfer usually occurred in solar thermal usages is the aim of the present study. This type of combined heat transfer in heat exchangers filled with a fluid saturated cellular porous medium is investigated. The flow is modeled by the Darcy–Brinkman equation. The steady state model of this combined heat transfer is solved semi-analytically based on the homotopy perturbation method (HPM) and numerically based on the finite difference method. No analytical solution has been previously proposed for the problem. Effects of porous medium shape parameter (s) and radiation parameters (T_r and λ) on the thermal performance are analyzed. Furthermore, a discussion on the accuracy and limitations of the HPM in this kind of problems is represented. This study shows that semi-analytical methods (like HPM, VIM, DTM, and HAM) can be used in simulation and prediction of thermal performance of solar energy harvesting systems.

1. Introduction

The concept of porous media plays a vital role in many engineering problems such as petroleum engineering (oil and gas flow in reservoirs), material science, filtration, acoustics, geomechanics, soil mechanics, rock mechanics, drying, and storage of absorbed solar energy. Today, porous media are used in solar collectors to increase the overall efficiency, in the solar room of green houses to heat the inside air, and as packed beds to store the solar heat for nights. Despite all advances and experimental, theoretical, and computational efforts in this area, scientists are still far from quite understanding all phenomena taking place in the porous medium because of some restrictions such as nonlinear nature of governing equations. Many studies have been conducted by researchers on investigation of forced convection in a channel filled with a saturated porous medium. Vafai and Kim [1] considered a fully developed forced convection in a porous channel bounded by parallel plates and obtained exact solution for both velocity and temperature fields. In their study, the properties of the porous medium and fluid were assumed to be isotropic and homogenous. Nakayama and Shenoy [2] investigated non-Darcy forced convective heat transfer in a channel confined by two parallel walls subjected to uniform heat flux in a highly porous medium saturated with a non-Newtonian power-law fluid. They carried out a numerical integration utilizing the Brinkman–Forchheimer extension of the Darcy model to study the effects of pseudoplasticity, Brinkman, and Forchheimer terms on the heat transfer characteristics. Nield and Kuznetsov [3] presented an analytical method in order to study forced convection in a plane channel occupied by a saturated bi-disperse porous medium, coupled with conduction in plane slabs bounding the channel. They considered effects of thermal parameter such as Péclet and Nusselt numbers. They also resulted that the effect of the finite thermal resistance due to the slabs is to reduce both the heat transfer to the porous medium and the degree of local thermal non-equilibrium. Alazmi and Vafai [4] conducted a numerical study on forced convection in a composite channel between parallel plates with different boundary conditions at the interface. They found effects of different boundary conditions on

* Corresponding author. Tel./fax: +98 231 3354122.
E-mail addresses: dehghan.maziar@gmail.com, m-dehghan@aut.ac.ir (M. Dehghan), u3f.r.mech@gmail.com (Y. Rahmani), ddg_davood@yahoo.com (D. Domiri Ganji), s_sadodin@iust.ac.ir (S. Saedodin), msvalipour@semnan.ac.ir (M.S. Valipour), samanrashidi3983@gmail.com (S. Rashidi).

http://dx.doi.org/10.1016/j.renene.2014.08.044
0960-1481/

Nomenclature

A	a differential operator
B	a boundary operator
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
Da	Darcy number, K/H^2
ddy	grid-size expansion factor
f	a known function
G	negative of the applied pressure gradient in flow direction (Pa m^{-1})
H	half of the channel gap (m)
L	linear part
K	permeability of the medium (m^2)
k	effective thermal conductivity of the medium (W m^{-1} K^{-1})
k_c	molecular thermal conductivity (W m^{-1} K^{-1})
k_f	thermal conductivity of fluid phase (W m^{-1} K^{-1})
k_r	radiative thermal conductivity (W m^{-1} K^{-1})
k_s	thermal conductivity of solid phase (W m^{-1} K^{-1})
M	viscosity ratio
N	non-linear part
n	number of iterations
Nu	Nusselt number
p	HPM parameter
q''_w	heat flux at the wall (W m^{-2})
r	variable of the domain Ω
s	porous media shape parameter
T	temperature (K)
T_m	bulk mean temperature (K)
T_r	temperature variation parameter (Eq. (20))
T_w	wall temperature (K)
u	dimensionless velocity; an arbitrary function in HPM introduction
u^*	velocity (m s^{-1})
$\widehat{u}$	normalized velocity
u^*_m	mean velocity (m s^{-1})
v	solution of Eq. (27)
x^*, y^*	dimensional coordinates (m)
y	dimensionless coordinate

Greek letters

β_R	Rosseland mean extinction coefficient (m^{-1})
Γ	boundary of the domain
θ	dimensionless temperature
λ	radiation parameter (Eq. (20))
μ	fluid viscosity (kg m^{-1} s^{-1})
μ_{eff}	effective viscosity in the Brinkman term (kg m^{-1} s^{-1})
ν	an arbitrary dependent parameter used in Eq. (38)
σ	Stefan–Boltzmann coefficient (W m^{-2} K^{-4})
ρ	fluid density (kg m^{-3})
ϕ	porosity of the medium
Ω	domain of problem

Subscripts

i	index
f	fluid phase
m	mean
s	solid phase
w	wall

the Nusselt, Reynolds, and Darcy numbers. Effects of viscous dissipation and boundary conditions on forced convection in a channel occupied by a saturated porous medium were studied by Hooman and Gurgenci [5]. Ozgen et al. [6] experimentally investigated a device for inserting an absorbing plate made of aluminum cans into the double-pass channel in a flat-plate solar air heater (SAH). They showed that their method substantially improved the collector efficiency by increasing the fluid velocity and enhancing the heat-transfer coefficient between the absorber plate and air. Also, Esen et al. [7,8] analyzed the thermal behavior of solar air heater (SAH) using least-squares support vector machine (LS-SVM), artificial neural network (ANN) and wavelet neural network (WNN) methods [9,10]. Boutin and Gosselin [11] numerically studied a vertical open-ended channel filled with a porous medium, with an imposed heat flux and a heat loss coefficient on one of its walls. They developed correlations for optimal pressure drop to be imposed by the fan and maximal energy recovery, as a function of the Rayleigh number, the channel aspect ratio, and the heat loss coefficient to be used in solar wall and solar chimney applied for ventilation and preheating of makeup air in buildings.

Nield and Kuznetsov [12] investigated a combined conductive–convective–radiative process in a channel occupied by a saturated cellular porous medium. Nield and Kuznetsov [12] showed that the Nusselt number increases at the case of variable conductivity arising from the radiative heat transfer. Dehghan et al. [13] investigated the flow and heat transfer in a fluid saturated porous medium bounded by iso-thermal parallel plates based on the perturbation and successive approximation methods analytically. They proposed a new dimensionless group representing the intensity of the local thermal non-equilibrium (LTNE) condition. Dehghan et al. [14] recently analyzed the performance of a tube heat exchanger filled with porous media based on numerical and analytical approaches at both iso-thermal and iso-flux thermal boundary conditions. They presented analytical expressions for the normalized velocity and the dimensionless temperature of the medium. Mahmoudi [15] numerically investigated the effects of thermal radiation from the solid phase on the temperature differential and the rate of heat transfer in a pipe partially filled with a porous material using discrete ordinate method (DOM) to compute the radiative heat flux. Zamzamian et al. [16] performed an experimental study to investigate the effect of Cu nanoparticle on the efficiency of a flat-plate solar collector. They found that by increasing the nanoparticle weight fraction, the efficiency of the collector was improved.

Despite the fact that many of thermal and fluid phenomena are expressed by nonlinear equations, only a few methods are able to solve them. In recent years, semi-analytical techniques are widely used for solving nonlinear equations because of their simple algorithms and capabilities in the solution. Ganji and Sadighi [17] used two semi-analytical techniques (variational iteration method and homotopy-perturbation method) in order to solve nonlinear heat transfer equations in porous media. They presented some comparisons between these methods and investigated the abilities and disabilities of these techniques for solving heat transfer nonlinear equations. Homotopy perturbation method (HPM) is one of the most well-known semi-analytical methods for solving nonlinear equations arising in engineering, especially in porous medium analyses. The HPM is introduced by Ji-Huan He of Shanghai University in 1998 [18]. The semi-analytical methods, especially the homotopy perturbation method, are applied in porous medium problems by many researchers [19–21].

In the present study, flow and heat transfer in a fluid saturated cellular porous medium bounded by two infinite parallel-plates at