Journal of Molecular Liquids 195 (2014) 230–239

Contents lists available at ScienceDirect

Journal of Molecular Liquids

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

Nanofluid flow and heat transfer in an asymmetric porous channel with expanding or contracting wall

M. Hatami [a,b], M. Sheikholeslami [a,c], D.D. Ganji [a,*]

[a] Department of Mechanical Engineering, Babol University of Technology, P.O. Box 484, Babol, Islamic Republic of Iran
[b] Esfarayen University, Engineering and Technical College, Department of Mechanical Engineering, Esfarayen, North Khorasan, Iran
[c] Department of Mechanical Engineering, University of Mazandaran, Babolsar, Iran

ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 19 February 2014
Accepted 23 February 2014
Available online 11 March 2014

Keywords:
Nanofluid
Porous channel
Heat transfer
Expansion ratio
GM
LSM

ABSTRACT

In this study, the least square method (LSM) and the Galerkin method (GM) are used to simulate flow and heat transfer of nanofluid flow between two parallel plates. One of the plates is externally heated, and the other plate, in which coolant fluid is injected through it, expands or contracts with time. The fluid in the channel is water containing different nanoparticles (Cu, Ag and Al_2O_3). The effective thermal conductivity and viscosity of the nanofluid are calculated by the Maxwell–Garnetts (MG) and Brinkman models, respectively. The effects of the nanoparticle volume fraction, Reynolds number, expansion ratio and power law index on flow and heat transfer are investigated. The results show that the Nusselt number increases with an increase of the nanoparticle volume fraction and Reynolds number. Also it can be found that in order to reach the maximum Nusselt number, copper should be used as a nanoparticle.

1. Introduction

Fluid heating and cooling are important in many industrial fields such as power plant operations, manufacturing and transportation. Effective cooling techniques are absolutely needed for cooling any sort of high energy device. Common heat transfer fluids such as water, ethylene glycol, and engine oil have limited heat transfer capabilities due to their low heat transfer properties. In contrast, metal thermal conductivities are up to three times higher than fluids, so it is naturally desirable to combine the two substances to produce a heat transfer medium that behaves like a fluid, but has the thermal conductivity of a metal. Recently several studies are investigating nanofluids. The problem of laminar nanofluid flow in a semi-porous channel in the presence of a transverse magnetic field was investigated analytically by Sheikholeslami et al. [1]. Their results showed that velocity boundary layer thickness decreases with an increase of Reynolds number and increases as the Hartmann number increases. Soleimani et al. [2] studied natural convection heat transfer in a semi-annulus enclosure filled with a nanofluid using the control volume based finite element method. They found that the angle of turn has an important effect on the streamlines, isotherms and maximum or minimum values of the local Nusselt number. A steady magneto-hydrodynamic free convection boundary layer flow past a vertical semi-infinite flat plate embedded in water filled with a nanofluid has been theoretically studied by Hamad et al. [3]. They found that Cu and Ag nanoparticles proved to have the highest cooling performance for this problem. Heat transfer of a nanofluid flow which is squeezed between parallel plates was investigated analytically using a homotopy perturbation method (HPM) by Sheikholeslami and Ganji [4]. They reported that the Nusselt number has a direct relationship with nanoparticle volume fraction, the squeeze number and Eckert number when two plates are separated but it has a reverse relationship with the squeeze number when two plates are squeezed. The MHD effect on natural convection heat transfer in an enclosure filled with a nanofluid was studied by Sheikholeslami et al. [5]. Their results indicated that the Nusselt number is an increasing function of the buoyancy ratio number but it is a decreasing function of the Lewis number and Hartmann number. Three dimensional heat and mass transfer in a rotating system using a nanofluid was investigated by Sheikholeslami and Ganji [6]. They concluded that the Nusselt number has a direct relationship with the Reynolds number while it has a reverse relationship with rotation parameter, magnetic parameter, Schmidt number, thermophoretic parameter and Brownian parameter. Free convection heat transfer in a concentric annulus between a cold square and heated elliptic cylinders in the presence of a magnetic field was investigated by Sheikholeslami et al. [7]. They found that the enhancement in heat transfer increases as the Hartmann number increases but it decreases with an increase of the Rayleigh number. Nanofluid flow and heat transfer has become a favorite topic in recent years [8–27].

* Corresponding author.
E-mail addresses: m.hatami2010@gmail.com (M. Hatami), mohsen.sheikholeslami@yahoo.com (M. Sheikholeslami), ddg_davood@yahoo.com (D.D. Ganji).

http://dx.doi.org/10.1016/j.molliq.2014.02.024
0167-7322/

Nomenclature

A	wall permeability
A_{1-4}	Constant parameters in nanofluids
a	Distance between parallel plates
$a(t)$	Expand or contract function
C_p	Specific heat in constant pressure
c_{1-4}	Constants in trial function
$F(\eta)$	Stream function variable
$f(\eta)$	Stream function variable [F/R]
k	Thermal conductivity
m	Temperature power index
Nu	Nusselt number
p	Pressure
q	Heat transfer
R	Reynolds number
$R(x)$	Residual function
t	Time
T	Temperature
u	Velocity in x direction
$\tilde{u}$	Trial function
v	Velocity in y direction
$W(x)$	Weighted function
x	Horizontal axes coordinate
y	Vertical axes coordinate

Greek symbols

α	Expansion ratio
μ	Viscosity
φ	Nanoparticle volume fraction
ρ	Density
Ψ	Stream function
η	Non-dimensional y direction [y/a]

Subscripts

f	Fluid
nf	Nanofluid
s	Solid
w	Wall

The flow between two porous parallel plates has received considerable attention in the past few years. The earliest work of steady flow across permeable and stationary walls can be traced back to Berman [28], who showed that the flow equations can be reduced to a single fourth-order nonlinear ordinary differential equation which includes the Reynolds number, and an associated solution can be obtained. Debruge and Han [29] studied a problem concerning heat transfer in channel flow, which can be considered as an application of previous works. They analyzed a method for cooling turbine blades in order to increase the resistance of the blades against the hot stream around the blades. Goto and Uchida [30] analyzed the laminar incompressible flow in a semi-infinite porous pipe whose radius varied with time. Dinarvand and Rashidi [31] got analytical approximate solutions for the viscous flow through expanding or contracting gaps with permeable walls.

There are some simple and accurate approximation techniques for solving differential equations called weighted residuals methods (WRMs). Collocation, Galerkin and least square methods are examples of the WRMs which Stern and Rasmussen [32] used for solving a third order differential equation. Also, Vaferi et al. [33] studied the feasibility of applying the orthogonal collocation method to solve a diffusivity equation in the radial transient flow system. Hendi and Albugami [34] used collocation and Galerkin methods for solving a Fredholm–Volterra integral equation. Recently the least square method was introduced by Aziz and Bouaziz [35] for predicting the performance of a longitudinal fin [36]. They found that the least square method is simple, compared with other analytical methods. Shaoqin and Huoyuan [37] developed and analyzed least-square approximations for the incompressible magneto-hydrodynamic equations. Asymmetric laminar flow and heat transfer of a nanofluid between contracting rotating disks were investigated by Hatami et al. [38]. Their results indicated that the temperature profile becomes more flat near the middle of two disks with the increase of injection but an opposite trend is observed with an increase of expansion ratio. In the recent decade, analytical methods were applied successfully in various scientific fields [39–46].

In this study, the purpose is to solve nonlinear equations of nanofluid flow and heat transfer in an asymmetric porous channel through the GM and LSM. The effect of an active parameter such as the volume fraction of a nanofluid, Reynolds number, expansion ratio and power law index on the flow and heat transfer characteristics has been examined.

2. Governing equations

The unsteady flow between two parallel flat plates is considered as shown in Fig. 1. The wall, which coincides with the x axis, is stationary and heated externally. In order to cool the heated wall, cooled fluid is injected with velocity v_w uniformly from the other plate, which expands or contracts at a time-dependent rate $a(t)$. Take y to be perpendicular to the plates and assume u and v to be the velocity components in the x and y directions respectively. In this perspective the flow field may be assumed to be a stagnation flow. The nanofluid is a two component mixture with the following assumptions: incompressible; no-chemical reaction; negligible radiative heat transfer; nano-solid-particles and the base fluid are in thermal equilibrium and no slip occurs between them. The thermophysical properties of the nanofluid are given in Table 1. Under these assumptions, the Navier–Stokes equations are [1]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

$$\rho_{nf}\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial v}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right), \tag{2}$$

$$\rho_{nf}\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial v}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right), \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_{nf}}{\left(\rho C_p\right)_{nf}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right). \tag{4}$$

Here u and v are the velocities in the x and y directions respectively, T is the temperature, and P is the pressure; the effective density ρ_{nf}, the effective heat capacity μ_{nf} of the nanofluid, the effective heat capacity

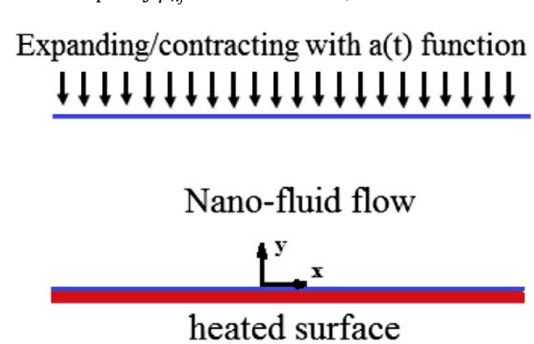

Fig. 1. Schematic of the problem.