Advanced Powder Technology 27 (2016) 564–574

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Heat transfer and pressure drop characteristics of nanofluid in unsteady squeezing flow between rotating porous disks considering the effects of thermophoresis and Brownian motion

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A R T I C L E I N F O

Article history:
Received 7 August 2015
Received in revised form 8 February 2016
Accepted 9 February 2016
Available online 15 February 2016

Keywords:
Nanofluid
Two-phase model
Pressure drop
Rotating disk
Squeezing flow
Magnetohydrodynamic (MHD)
Heat transfer

A B S T R A C T

In this study, the unsteady three dimensional nanofluid flow, heat and mass transfer in a rotating system in the presence of an externally applied uniform vertical magnetic field is investigated. This study has different applications in rotating magneto-hydrodynamic (MHD) energy generators for new space systems and also thermal conversion mechanisms for nuclear propulsion space vehicles. The important effects of Brownian motion and thermophoresis have been included in the model of nanofluid. The governing equations are non-dimensionalized using geometrical and physical flow field-dependent parameters. The velocity profiles in radial, tangential and axial directions, pressure gradient, temperature and concentration distributions are obtained. The effects of different governing parameters namely: Reynolds number, rotation parameter, magnetic parameter, Prandtl number, Schmidt number, thermophoretic parameter and Brownian motion parameter on all nanofluid velocity components, temperature and concentration distributions, pressure gradient, Nusselt number and Sherwood number are displayed through tables and graphs and the results are discussed in detail.

1. Introduction

Enhancement of heat transfer performance in many industrial fields such as power, manufacturing and transportation, is an essential topic from an energy saving perspective. A recent way of improving the performance of thermal systems is to suspend metallic nanoparticles in the base fluid. This is one of the most modern and applicable methods for increasing the coefficient of heat transfer. It is expected that the ultrafine solid particle is able to increase the thermal conductivity and heat transfer performance since the thermal conductivity of solid metals is higher than that of base fluids such as water and oil. For example, copper has a thermal conductivity 700 times grater than water and 3000 times greater than engine oil. The term "nanofluid" refers to a liquid containing a suspension of solid particles (nanoparticles) in the range of sizes from 1 nm to 100 nm. The term was coined by Choi [1]. Numerous models and methods have been proposed by different authors to study convective flows of nanofluids. Khanafer et al. [2] initially conducted a numerical investigation on heat transfer enhancement due to adding nano-particles in a differentially heated enclosure. Rashidi et al. [3] considered the analysis of the second law of thermodynamics applied to an electrically conducting incompressible nanofluid flowing over a porous rotating disk. This field of science became very popular for several authors [4–12].

Squeezing flows between rigid rotating bodies have many industrial and engineering applications such as hydrodynamic machines, gas turbine engines, blood flow due to expansion and contraction of vessels and electronic devices having rotary parts. Squeezing flows are caused by the application of normal stresses to the running surfaces. The pioneering formulation and research on hydrodynamic flow due to an infinite rotating disk was done by Von Kármán [13]. He introduced an elegant transformation that enabled the Navier–Stokes equations for an isothermal, impermeable rotating disk to be reduced to a system of coupled ordinary differential equations. Hydromagnetic nanofluid flow and heat transfer between two horizontal plates in a rotating system, where the lower plate is a stretching sheet and the upper is a porous solid plate, was analyzed by Sheikholeslami et al. [14]. Rath and Iyengar [15] discussed the unsteady flow of a viscous incompressible fluid produced by a porous disk which was rotating with a

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http://dx.doi.org/10.1016/j.apt.2016.02.011
0921-8831/

Nomenclature

a	half distance between disks (m)
B	constant applied magnetic field (A/m)
B_0	magnetic flux density (kg/s^2 A)
C	dimensionless concentration
C_p	specific heat at constant pressure (kJ/kg K)
D_B	Brownian diffusion coefficient (kg/m s)
D_T	thermophoretic diffusion coefficient (kg/m s K)
F	dimensionless axial velocity
f, g	dimensionless functions
G	dimensionless azimuthal velocity
k	thermal conductivity (W/m K)
M	magnetic parameter
Nb	Brownian motion parameter
Nt	thermophoresis parameter
Nu_r	local Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q_w	surface heat flux (W/m^2)
r	radial component (m)
Re	Reynolds number
Sh_r	local Sherwood number
s	permeability parameter
s_w	surface mass flux (kg/m^2 s)
T	fluid temperature (K)
u, v, w	velocity components (m/s)
x	dimensionless axial distance (m)
z	axial component (m)

Greek symbols

α	thermal diffusivity (m^2/s)
σ	electrical conductivity (A^2 s^3/m^3 kg)
ϕ	nanoparticle volume fraction
Ω	constant angular velocity (rad/s)
θ	dimensionless temperature
υ	kinematic viscosity (m^2/s)
ζ	tangential component (rad)
μ	dynamic viscosity (kg/m s)
ρ	fluid density (kg/m^3)

Subscripts

f	fluid
p	nanoparticles
w	condition at the surface of the disk

Superscripts

$'$	differentiation with respect to x

time-dependent angular velocity. Rashidi et al. [16] looked at analytic approximate solutions for steady flow over a rotating disk in a porous medium with heat transfer by means of famous Homotopy Analysis Method (HAM). Khaled and Vafai [17] considered the oscillatory squeezed flow of a thin viscous film in a channel with its upper plate inclined and found that the fluctuations have great impact on axial and normal velocities. Ghori et al. [18] utilized homotopy perturbation method to investigate the squeezing flow of Newtonian fluid. The same problem was considered by Ran et al. [19] and explicit series solution was obtained by means of homotopy analysis method.

Most of the above studies assumed that there aren't any slip velocities between nanoparticles and fluid molecules and assumed that the nanoparticle concentration is uniform. It is believed that in natural convection of nanofluids, the nanoparticles could not accompany fluid molecules due to some slip mechanisms such as Brownian motion and thermophoresis, so the volume fraction of nanofluids may not be uniform anymore and there would be a variable concentration of nanoparticles in a mixture. Buongiorno [20] introduced and discussed seven slip mechanisms in nanofluids. He explained the relative importance of them in a comprehensive study. Nield and Kuznetsov [10] studied the natural convection in a horizontal layer of a porous medium. Their analysis revealed that for a typical nanofluid with large Lewis number, the prime effect of the nanofluid is via a buoyancy effect coupled with the conservation of nanoparticles, while the contribution of nanoparticles to the thermal energy equation being a second-order effect. Sheikholeslami et al. [21] used heatline analysis to simulate two phase simulation of nanofluid flow and heat transfer. Their results indicated that the average Nusselt number decreases as buoyancy ration number increases until it reaches a minimum value and then starts increasing. Hassani et al. [22] investigated the problem of boundary layer flow of a nanofluid past a stretching sheet. They found that the reduced Nusselt number decreases with the increase in Prandtl number for many Brownian motion parameters. In a recent work, two phase modeling of nanofluid in a rotating system was studied by Sheikholeslami and Ganji [23]. Their results indicate that skin friction parameter increases with augmentation of Reynolds number and rotation parameter but it decreases with increase of injection parameter.

Recently, there have been several published numerical studies on the modeling of squeezing flow and effect of using nanofluids on heat transfer enhancement. Domairry and Aziz [24] examined the magnetohydrodynamic flow of a viscous fluid squeezed between two parallel disks and the effects of suction and injection were analyzed. The three dimensional unsteady MHD flow in a rotating channel with lower wall stretching and upper plate squeezing was studied by Munawar et al. [25]. Hussain et al. [26] used both analytical and numerical approaches to investigate the flow and heat transfer characteristics between two parallel disks with slip velocity and temperature jump conditions. Sheikholeslami et al. [27] studied a steady squeezing nanofluid flow and heat transfer. They investigated the effects of the squeeze number, the nanofluid volume fraction and Eckert number on Nusselt number and skin friction coefficient. Analysis of entropy generation effects in squeezing flow was studied by some researchers such as Rashidi et al. [3,28] and Butt and Ali [29]. Domairry and Hatami [30] investigated squeezing Cu–water nanofluid flow between two parallel plates using a differential transformation method (DTM) and numerical method. This problem was also extended by Hatami et al. [31] for a laminar flow and heat transfer of a nanofluid between contracting rotating disks and by Sheikholeslami and Ganji [32] for three dimensional nanofluid flow and heat transfer in a rotating system in the presence of magnetic field.

There are generally two approaches for modeling of nanofluids: single phase and two phase models. Since the single phase model is also simpler to implement and requires less computer memory and CPU time, most of the earlier researchers preferred to consider this model. The main purpose of this work is to apply two phase flow model for simulating nanofluid flow, heat and mass transfer in a rotating system in the presence of magnetic field considering ther-