International Journal of Heat and Mass Transfer 81 (2015) 681–694

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient buoyancy-opposed double diffusive convection of micropolar fluids in a square enclosure

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ARTICLE INFO

Article history:
Received 3 July 2014
Received in revised form 2 September 2014
Accepted 10 October 2014
Available online 22 November 2014

Keywords:
Micro polar fluid
Double diffusion
Vortex viscosity parameters
Critical buoyancy ratio
Operator splitting algorithm

ABSTRACT

The present study considers transient buoyancy-opposed double diffusive free convection of a micropolar fluid consisting of rigid and non-deformable particles suspension with its own rotation in a square enclosure. The governing equations are written in terms of the primitive variables and a numerical solution of the complete set of nonlinear equations has been done without any scaling to the flow terms. The modified Marker and Cell (MAC) method is used for the solution of the variables in the primitive form with the help of the Alternating Direction Implicit (ADI) scheme. In order to handle effectively the advection terms, the gradient dependent consistent hybrid upwind scheme of second order (GDCHUSSO) and the operator-splitting algorithm have been employed. A parametric study is conducted to illustrate the effects of the Rayleigh number, Prandtl number, buoyancy ratio and the vortex viscosity parameter. Interesting features of stability at critical buoyancy ratios with the inclusion of the vortex viscosity parameter is reported. Detailed distributions of isotherms, isoconcentrations, flow lines and microrotation lines are provided to reveal the concealed physics of the complex phenomenon. A power spectrum analysis and phase plane maps are provided to bring clarity about the instability involved in the phenomenon. Correlations have been developed for the average Nusselt and Sherwood numbers based on the computed results.

1. Introduction

The micropolar fluid theory is used to describe those fluids whose micro-constituents play a pivotal role in affecting the hydrodynamics of the flow. The micro-structure of these fluids is modeled as being rigid and randomly oriented. The Navier–Stokes equations for a Newtonian fluid have failed to describe the flow behavior of the fluids with suspensions which are classified as non-Newtonian fluids. A glimpse to the history shows that, Eringen [1] is the pioneer who introduced the theory of micropolar fluids by giving the concept of micro-rotation. He defined various material parameters and added other constitutive equations for non-Newtonian fluids in the Newtonian fluid equations. Ariman et al. [2] have shown that the micropolar fluid theory is applicable for all linear, viscous and isotropic fluids. Various polymeric fluids, colloidal fluids, animal blood, liquid crystals are modeled using the micropolar fluid theory. Ahmadi [3] has studied the self-similar solution of incompressible micropolar fluid boundary layer flow over a semi-infinite flat plate. He has observed that micro-rotation vector is proportional to the fluid shear stress, and found that the micro-inertia density varies as the square of the perpendicular distance from the surface without boundary layer. Jena and Mathur [4] have reported on the similarity solutions for laminar free convection flow of a thermo-micropolar fluid flow past a non-isothermal vertical flat plate. Jena and Bhattacharya [5] have investigated the effect of micro-structure on the thermal convection in a rectangular box of fluid heated from below. Sharma and Gupta [6] have considered the effect of medium permeability on the thermal convection in micropolar fluids. They reported that the presence of coupling between thermal and micropolar effects brings over stability in the system. Hsu and Chen [7] have studied the steady, laminar, natural convection of micropolar fluids in a rectangular enclosure. They have solved the governing equations using the cubic spline collocation method. They have observed a significant effect of the micro-structures on the convective heat transfer. It was reported that an increase in the vortex viscosity parameter decreases the heat transfer rate whereas an increase in the spin gradient viscosity increases the heat flux. Hsu and Hsu [8] have made a numerical study on the natural convection of micropolar

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.030
0017-9310/

Nomenclature

C	solute concentration (kg m^{-3})
C_p	specific heat capacity (J kg^{-1} K^{-1})
D	mass diffusivity (m^2 s^{-1})
g	acceleration due to gravity (m s^{-2})
i,j	nodal index
k	thermal conductivity (W m^{-1} K^{-1})
L	length of the cavity (m)
N	angular velocity (s^{-1})
$\mathfrak{N}$	microrotation vector
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
P	dimensionless pressure
Pr	Prandtl number
$\mathfrak{R}$	vortex viscosity parameter/material parameter
Ra	thermal Rayleigh number
Ra_s	solutal Rayleigh number
Sh	Sherwood number
$\overline{Sh}$	average Sherwood number
T	absolute temperature (K)
t	time (s)
u,v	dimensional velocity component (m s^{-1})
U,V	dimensionless velocity component
x,y	dimensional coordinate (m)
X,Y	dimensionless coordinate

Symbols

α	thermal diffusivity (m^2 s^{-1})
β_T	coefficient of thermal expansion (K^{-1})
β_C	coefficient of solutal expansion (m^3 kg^{-1})
Θ	dimensionless temperature
Φ	dimensionless concentration
μ	dynamic viscosity (kg m^{-1} s^{-1})
v	kinematic viscosity (m^2 s^{-1})
τ	dimensionless time
ρ	density, (kg m^{-3})

Subscripts

L	lower
H	higher
0	reference

fluids in tilting enclosures with heat sources. Takhar et al. [9] have studied the micropolar fluid flow and heat transfer between two porous discs using the finite-element method. They have obtained a numerical solution for the governing equations and found that an increase in the micropolar concentration increases both the heat transfer and axial velocity but reduces the skin friction. Srinivasacharya et al. [10] have studied the unsteady Stokes flow of a micropolar fluid between two parallel porous plates. They observed that an increase in the suction to injection ratio increases the skin friction. Wang and Cheng [11] have studied the transient behavior of the laminar mixed convection in a micropolar fluid flow over a vertical wavy surface. They reported that for micropolar fluids, the skin friction coefficient is lower than that for Newtonian fluids for smaller values of the vortex viscosity parameter but higher for larger values of the vortex viscosity parameter. They also reported that the heat transfer rate of a micropolar fluid is always less than that for a Newtonian fluid. Chamkha et al. [12] have studied the fully developed free convection flow of a micropolar fluid in a vertical parallel channel and presented the solution both analytically and numerically. They have considered an asymmetrical heating condition and used the implicit finite difference method for the numerical solution. They found that an increase in the wall temperature increases the velocity and micro-rotation profiles, and an increase in the vortex viscosity reduces the velocity profile. Chamkha et al. [13] have also studied the fully developed mixed convection flow of a micropolar fluid. Chamkha et al. [14] have reported on the three-dimensional micropolar fluid flow due to a stretching surface and found that the boundary layer structure is affected by the material parameters. Kim and Lee [15] have reported an analytical study on magneto-hydrodynamics (MHD) oscillatory flow of a micropolar fluid over a vertical porous plate. They have studied the effects of micro-gyration vector on the flow when a magnetic field is applied transversely to the plate. They found that increasing the magnetic field decreases the velocity distribution in the boundary layer. They observed that the velocity gradient near the porous plate decreases as the vortex viscosity increases. Duwairi and Chamkha [16] have studied the transient free convection flow of a micropolar fluid over a vertical surface. They have noticed that the vortex viscosity has a direct effect on the velocity and temperature profiles inside the boundary layer and an inverse effect on fluid rotation. Also, increasing the micropolar material parameter increases the coefficient of friction. Chen [17] has investigated the transient analysis of natural convection in a micropolar fluid to determine the heat transfer between concentric and vertically eccentric spheres with specified isothermal boundary conditions. He found that up to a low Rayleigh number, the skin friction acting on the wall for a Newtonian fluid is stronger than the same for a micropolar fluid, however; with a high Rayleigh number, the behavior is reversed. Gorla et al. [18] have studied mixed convection boundary layer flow of a micropolar fluid along a vertical cylinder. They found that as the Prandtl number increases, the surface friction factor decreases, the surface heat transfer rate increases and the wall couple stress decreases with the stream-wise distance. Lok et al. [19] reported on non-orthogonal stagnation-point flow of a micropolar fluid. Aydin and Pop [20] have considered natural convection of a micropolar fluid in a closed geometry. They have done the analysis in a differentially heated enclosure filled with a micropolar fluid by numerically solving the governing equations using the finite difference method. They observed that irrespective of the value of the Prandtl number, the effect of the micropolar material parameter is found to decrease the heat transfer. The decrease in the heat transfer is due to increasing the micropolar material parameter, which is more significant for higher values of the Rayleigh number. Ziabakhsh and Domairry [21] have used the Homotopy Analytic Method (HAM) to study the micropolar flow in a porous channel with high mass transfer. Also Joneidi et al. [22] have studied the micropolar flow in a porous channel with high mass transfer. They solved the governing equations using the Optical Homotopy Asymptotic Method (OHAM), and observed that with the increase in the Reynolds number, there is an increase in the stream-wise and transverse velocities. Zadravec et al. [23] have studied the natural convection of a micropolar fluid in an enclosure with the boundary-element method to derive the governing equations in differential and integral forms. They observed that the local and average Nusselt numbers decrease as the micropolar material parameter increases. Damseh et al. [24] have studied combined heat generation and first-order chemical reaction effects on micropolar fluid flowing over a uniformly stretched permeable surface. Ashraf et al. [25] have numerically studied asymmetric flow of a