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Thermosolutal hydromagnetic convection of power law fluids in an enclosure with periodic active zones

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ABSTRACT

A finite volume technique based double diffusive natural convection of power-law fluid in an enclosure has been studied numerically in the presence of magnetic field due to different physical parameters such as Rayleigh number (*Ra*), Lewis number (*Le*), Hartmann number (*Ha*) and Prandtl number (*Pr*). The flow is generated by the combined mechanism of a time periodic thermal and solutal gradient acts along the vertical walls. The combined buoyancy effect due to thermal and species diffusion plays a key role on the flow characterisation. The study dealt with the effect of pertinent parameters on fluid flow, heat and mass transfer in case of a laminar flow regime. The apparent power law indices and magnetic field strengths are varied using the non-Newtonian power law forms. The relevant results are presented in terms of streamlines, isotherms, isoconcentrations, average Nusselt number, Sherwood number and total entropy generation with the variation of power law index (n) from 0.2 to 1.8, Ra from 10^4 to 10^5, Ha from 0 to 20, Pr from 1 to 5 and buoyancy ratio (N) from -1 to 1. The entropy generation and Bejan number are determined to analyze the thermodynamic optimization of the conjugate double diffusive convection. It is observed that the average Nusselt and Sherwood number shows linear variation with the increase of amplitudes of the imposed sinusoidal temperature and concentration gradient and the fluctuation is found to be trivial. Also the results indicate that the power law index variation influences largely the rate of heat and mass transfer and average entropy generation. The magnetic field strength increases the strength of the fluid flow and also strongly supported by the increased values of n. It is found that with the decrement of flow behavior index n the buoyancy effect and the hydrodynamic behavior of the fluid is getting increased.

1. Introduction

In the past few decades; most of the researchers are focused on the non-Newtonian fluid flow, heat and mass transfer in enclosures due to its ample applications in many industrial such as polymer processing, petroleum product extraction, slurry transporting, chemical and fertilizer production, medicine and food processing, printing ink, paper making, paint and emulsion manufacturing and packing which requires the knowledge of non-Newtonian flows [1]. Generally, non-Newtonian fluids are classified into two main categories such as viscoinelastic and viscoelastic fluid. Most of the shear thickening materials are pseudo plastic (or dilatant) and the viscosity increases with the rate of shear strain. But for inelastic shear thinning fluid the extensional viscosity must decreases with the increase rate of tension thinning (extension) [2]. The pseudo plastic fluids have relatively smaller apparent viscosity at higher shear rates but at low shear rate, it is believed that the large molecular chains are randomly distributed and occupy large volumes in the fluid [3]. But, for the most of the pseudo plastic fluids, the viscosity decreases with temperature and increases with pressure. The density of this kind of fluid may changes, for which the density variation (except where they appear in terms multiplied by acceleration due to gravity) can be ignored and the Boussinesq's approximation (the difference in inertia is negligible but gravity is sufficiently strong to make the specific weight appreciably different between two fluids) is used for the case of buoyancy-driven flow (also known as natural convection).

Natural convection of power law fluid in an enclosures is one of the subjects of a great number of theoretical, experimental and numerical investigation due to its rapid applications in many fields (for example, in polymer industry, liquid-metal blankets are used in fusion reactors and for the crystal growth in industrial production of semiconductors, etc.) [4]. But most of the studies on natural

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Nomenclature

A	area (m^2)
B	magnetic field (Amp/m)
C	concentration (kg m^{-3})
D	mass diffusivity (m^2 s^{-1})
g	gravity (m s^{-2})
Ha	Hartmann number
k	thermal conductivity (W m^{-1} K^{-1})
k_p	flow consistency index (kg m^{-1} s^{n-2})
L	length of square cavity (m)
Le	Lewis number
N	buoyancy ratio $\left(\frac{Ra_S}{Ra_T}\right)$
Nu	Nusselt number
n	flow behavior index
P	pressure (N/m^2)
Pr	Prandtl number $\left(\frac{\nu}{\alpha}\right)$
R	gas constant
Ra	Rayleigh number
S	entropy
Sh	Sherwood number
T	temperature (K)
t	time (s)
(u, v)	velocity (m s^{-1})
$\mathbf{V}$	velocity vector
(x, y)	cartesian coordinate

Greek

α	thermal diffusivity (m^2 s^{-1})
β_T	thermal expansion coefficient (K^{-1})
β_s	concentration expansion coefficient (m^3 kg^{-1})
$\dot{\gamma}$	strain rate tensor (s^{-1})
$\nabla\cdot$	divergence operator
ρ	fluid density (kg m^{-3})
θ_m	dimensionless mean temperature
μ	dynamic viscosity (N s/m^2)
σ	electrical conductivity (S m^{-1})
τ	shear stress (N m^{-2})

Subscripts

T	temperature
C	concentration
s	solutal
$*$	dimensional quantity
m	normalized quantity

convection are restricted on inclusion of thermal gradients, but the concentration gradient plays a vital role in the above mentioned applications. Such type of flows (the combined mechanism of thermal and solutal gradients) is simply called double diffusive free convection flow [5]. Also, most of the studies dealt with a linear temperature density variation, but it is observed that this will never happen as the density of the water varies with temperature in a non-linear fashion. Keeping this point, Nithyadevi and Yang [6] studied the effect of double diffusive natural convection flow in an enclosure filled with water and found that the non-linear behavior of heat and mass transfer rate occurs due to the maximum density variation. The natural convection of power law fluid between two concentric isothermal cylinders studied numerically by Matin and Khan [7] and observed that heat transfer rate decreases with the increase of power law index. Kuznetsov and Sheremet [8] studied the transient double-diffusive natural convection in a cubical enclosure due to the effects of temperature and concentration gradients. They have found that stabilization of the concentration field occurs long before stabilization of the temperature field. A horizontal rectangular cavity filled with power law fluid subjected to cross gradients of temperature is studied both analytically and numerically by Lamsaadi et al. [9] and they observed that the fluid flow and heat transfer rate are quite different in case of power law fluid. Also, found that the shear-thinning behavior increases the fluid flow circulation and convection heat transfer rate but the shear-thickening gives the opposite effect. Major studies on natural convective heat transfer of non-Newtonian power law fluids are related to the effects of aspect ratio, Rayleigh and Prandtl numbers [10,11]. The numerical simulation of periodic flow oscillation for low Prandtl number fluids in rectangular enclosure was studied by Crunkleton et al. [12] and they observed that non periodic flows for rectangular cavity occurs when aspect ratio is 2.0.

A lot of research related to natural convection is modelled using non-Newtonian power law fluids in order to gain basic physical understandings, for which the double-diffusive natural convection in a partially active zone depends not only on the aspect ratio but also depends on its position of the heat and solutal sources of the enclosure, due to which it gives an optimum heat and mass transfer. In this aspect the double diffusive free convection of power law fluid in an enclosure is studied by Jena et al. [1] and they found that the maximum heat and mass transfer rates are occured in case of pseudo-plastic fluid as compared to Newtonian and dilatant fluid and they have also found that the middle-middle arrangement of heat source is optimum in case of thermally dominant flow. The double-diffusive natural convection in a partially active side walls was studied numerically by Nikbakhti and Rahimi [13] and observed that bottom-top combination of side walls provides the maximum heat transfer rate and minimum for the top-bottom combination. Nithyadevi et al. [14] studied the transient natural convection in a square cavity with partially active sides walls and observed that the middle position of hot wall enhance the heat transfer when $Gr < 4 \times 10^5$. Also, Nayak et al. [15] observed the maximum heat transfer rate at middle-middle combination of the thermally active zones along the side walls.

The buoyancy driven flow induced by the combined effect of thermal and solutal gradients are referred as double diffusive convection. Since, the temperature and solute of different diffusivities affect simultaneously the density variation and fluid motion has ripened into the subject of wide variety of applications such as oceanology, astrophysics, manufacturing, ventilation, chemical process, crystal growth, energy storage, material processing and food processing. In addition, several investigation of double diffusive convection for Newtonian/non-Newtonian fluids were conducted by researchers formulating different mathematical models dealing with different numerical approaches. The double diffusive convection of sinusoidally- varying temperature in a cylindrical horizontally-originated annulus was investigated numerically by Al-Amiri et al. [16]. They found that the heat transfer rate is increased with the amplitude and frequency of the heated inner cylinder. Groşan et al. [17] carried out a numerical investigation on double diffusive and thermophoresis effects in a wavy wall cavity filled with Newtonian fluid. They observed that the average rate of heat transfer is acting as an increasing function of Schmidt number and thermophoretic coefficient. On the other hand, it is actively possesses a decreasing function of buoyancy ratio and undulation number for Schmidt number greater than three. Natural