Linear instability of Nanofluid with helical force

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Abstract; The investigation focuses on the onset of convection in a horizontal layer saturated nanofluid with helical force. The non-dimensional governing equations is solved using the normal mode technique, resulting in an eigenvalue problem. The eigenvalue problem for linear instability is solved using the one-term Galerkin approach which gives the analytical expression for Rayleigh number. Neutral curves are drawn for both steady and oscillatory instability for all physical parameters.

Keywords: Thermal instability, Nanofluid, Eigenvalue Problem.

1.Introduction

Due to its practical uses in a range of geological processes, including liquid re-injection, migration, subsurface nuclear waste disposal, and drying processes, double-diffusive convective phenomena is a topic of great interest for researchers [6]-[22]. The double-diffusive instability of a Newtonian fluid in a horizontal layer has also been studied in great detail. Likewise, numerous materials exhibit non-Newtonian behavior, such as paints, mud, clay, honey, blood, and hair gel, making non-Newtonian fluid convective events intriguing [19]. Numerous models, including the power-law model, the Maxwell model, the Jeffrey model, and other viscoplastic fluid models, are available in the literature to analyse the characteristics of non-Newtonian fluids [19].

The beginning of convection in a porous layer saturated with Oldroyd fluid was covered by Malashetty and Swamy [11]. It was possible to derive the analytical conditions for finite amplitude, steady, and stable convections. Using the thermal non-equilibrium effect, Malashetty et al. [10] and Kumar and Bhadauria [9] extended the same problem. The double-diffusive convective motion of a Maxwell liquid was studied by Awad et al. [1]. They come to the conclusion that the critical Rayleigh number falls by using the Maxwell parameter as a stand-in. Wang and Tan [20] investigated convective instability for non-Newtonian liquid in a porous layer using a modified Maxwell-Darcy model. Internally heated double diffusive instability in a non-Newtonian form of coupled stress fluid flooded porous layer was examined by Gaikwad and Kouser [8]. They found that the internal Rayleigh number stabilizes the system.
Gaikwad and Dhanraj [7] investigated the effects of anisotropy and internal heating on the binary Maxwell liquid in a permeable layer. on a recent work, Yadav et al. [21] and some other researchers [2, 3, 4, 5, 12, 13]-[14, 15, 16, 17, 18] discovered the chemical reaction effect on the thermossolutal internally heated convection of a Maxwell fluid in a porous layer. They found that the Dam Kohler number has distinct effects on oscillatory and steady convection.

The current paper examines the beginning of helical force effect in a nanofluid. We write fundamental equations in section 2. Linear instability is covered in Section 3. The following parts provide the results and conclusions.

2.Mathematical formulation

Consider a heated, infinitely thin, horizontal layer of nanofluid with thickness $'d'$ that is confined by the planes $z = 0$ and $z = d$. It is assumed that each boundary wall is impermeable and has perfect heat conductivity. The volumetric fraction ϕ and temperature T of nanoparticles are assumed to be T_0 and ϕ_0 at $z = 0$ and T_1 and ϕ_1 at $z = d$, respectively $(T_0 > T_1)$. The assumed reference temperature is T_1. The governing equations are:

$$\nabla \cdot \mathbf{V} = 0, \tag{1}$$

$$\rho_0 \left(\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V}\right) = -\nabla P + \rho_0\, a\Omega d\, \mathbf{f} + [\phi \rho_p + (1-\phi)\rho_0(1-\beta(T-T_1))]\mathbf{g}, \tag{2}$$

$$\left(\frac{\partial}{\partial t} + (\mathbf{V} \cdot \nabla)\right)\phi = D_B \nabla^2 \phi + \frac{D_T}{T_1}\nabla^2 T, \tag{3}$$

$$\rho c \left(\frac{\partial}{\partial t} + (\mathbf{V} \cdot \nabla)\right) T = \kappa_T \nabla^2 T + \rho_p c_p \left[D_B \nabla\phi \cdot \nabla T + \frac{D_T}{T_1}\nabla T \cdot \nabla T\right]. \tag{4}$$

Where

$\mathbf{V}$ − velocity of nanofluid ; κ_T − thermal conductivity of nanofluid;
$a\Omega d$ − amplitude of model force ; T − temperature of nanofluid ;
c − nanofluid specific heat ; β − thermal expansion coefficient ;
ρ_f − density of base fluid ; ρ_p − nanoparticle density ;
ρ_{f_0} − base fluid density ; ϕ − volumetric fraction of nanoparticles ;
ρ − Density ; P − Pressure ;
$\hat{e_z} = (0,0,1)$ − unit vector along the vertical axis ; t − time ;
$\mathbf{f} = \hat{e_z}\,(curl(\mathbf{V}))_z - \dfrac{\partial(\hat{e_z} \times \mathbf{V})}{\partial z}$ − Helical force ;
ρ_0 − reference density
D_T − thermophoretic diffusion coefficient of nanoparticles,
D_B − Brownian diffusion coefficient of nanoparticles,
k_B − Boltzmann's constant,
κ_f − Thermal conductivity of the base fluid,
κ_p − Thermal conductivity of the nano particles,
μ_f − Viscosity of the base fluid,
d_p − Nanoparticle diameter.

Subject to the boundary conditions

$$\begin{aligned} &\mathbf{V} = 0,\ T = 1,\ \phi = 0 \ at\ z = 0, \\ &\mathbf{V} = 0,\ T = 0,\ \phi = 1 \ at\ z = 1. \end{aligned} \tag{5}$$

the following non-dimensional parameters are introduced:

$$(x', y', z') = \frac{1}{d}(x, y, z), \qquad t' = \frac{\alpha t}{d^2}, \qquad P' = \frac{d^2 P}{\mu \alpha},$$

$$(u', v', w') = \frac{d}{\alpha}(u, v, w), \qquad T' = \frac{T - T_1}{T_0 - T_1}, \qquad \phi' = \frac{\phi - \phi_0}{\phi_1 - \phi_0},$$

where $\alpha = \frac{1}{\rho C}$.

The non-dimensional form of Eqs. [1], [2], [3] and [4] are

$$\nabla' \cdot V' = 0, \tag{6}$$

$$\frac{1}{\mathrm{Pr}}\left(\frac{\partial \mathbf{V}'}{\partial t'} + (\mathbf{V}' \cdot \nabla')\mathbf{V}'\right) = \nabla' \mathrm{P}' + \nabla'^2 \mathbf{V}' - \mathrm{R_m}\,\hat{e_z} + \mathrm{R_T} \mathrm{T}'\,\hat{e_z} - \mathrm{R_n}\phi'\,\hat{e_z} + \mathrm{S_h}\, f' \tag{7}$$

$$\left(\frac{\partial}{\partial t'} + (\mathbf{V}' \cdot \nabla')\right)\phi' = \frac{\mathrm{N_A}}{\mathrm{Le}}\nabla'^2 \mathrm{T}' + \frac{1}{\mathrm{Le}}\nabla'^2\phi', \tag{8}$$

$$\left(\frac{\partial}{\partial t'} + (\mathbf{V}' \cdot \nabla')\right)\mathrm{T}' = \nabla'^2 \mathrm{T}' + \frac{\mathrm{N_B}}{\mathrm{Le}}(\nabla'\mathrm{T}' \cdot \nabla'\phi') + \frac{\mathrm{N_A N_B}}{\mathrm{Le}}(\nabla'\mathrm{T}' \cdot \nabla'\mathrm{T}'). \tag{9}$$

Where
$$\begin{cases} R_T = \frac{\rho_0 g \beta d^3 (T_0 - T_1)}{\mu\alpha} - \text{Rayleigh number;} \\ R_n = \frac{(\rho_p - \rho_{f_0})(\phi_1 - \phi_0) g d^3}{\mu\alpha} - \text{Concentration Rayleigh number;} \\ R_m = \frac{[\rho_p \phi_0 + \rho_{f_0}(1-\phi_0)] g d^3}{\mu\alpha} - \text{Basic density Rayleigh number;} \\ N_A = \frac{D_T (T_0 - T_1)}{D_B T_1 (\phi_1 - \phi_0)} - \text{Modified diffusivity ratio;} \\ N_B = \frac{\rho_p C_P}{\rho C}(\phi_1 - \phi_0) - \text{Modifiedparticledensityincrement;} \\ Pr = \frac{\nu}{\alpha} - \text{Prandtl number;} \\ Le = \frac{\alpha}{D_B} - \text{ Lewis number;} \end{cases}$$

2.1 Basic State

It is assumed that the basic state of the nanofluid is time independent and is described by

$$\mathbf{V}_b = 0, \qquad \phi_b = 0, \qquad T_b = 1 - z. \tag{10}$$

For small disturbances onto the basic state, we assume that

$$\mathbf{V}' = \mathbf{V}_b + \mathbf{V}, \qquad P' = P_b + P, \qquad T' = T_b + T, \qquad \phi' = \phi_b + \phi, \tag{11}$$

3.Linear Stability Analysis

By substituting Equation [11] into Equations [6]-[9], we obtain

$$\nabla \cdot \mathbf{V} = 0, \tag{12}$$

$$\frac{1}{Pr}\frac{\partial \mathbf{V}}{\partial t} = \nabla P + \nabla^2 \mathbf{V} - R_m\,\hat{e_z} + R_T T\,\hat{e_z} - R_n \phi\,\hat{e_z} + S_h\,\mathbf{f}', \tag{13}$$

$$\frac{\partial T}{\partial t} - w = \nabla^2 T + \frac{N_b}{L_e}\nabla\phi.\nabla T + \frac{N_a N_b}{L_e}\nabla T \cdot \nabla T, \tag{14}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Le}\nabla^2\phi + \frac{N_A}{Le}\nabla^2 T. \tag{15}$$

By Taking the third components of curl of [13]) and curl of curl of ([13]), we obtain,

$$\left(\frac{1}{Pr}\frac{\partial}{\partial t} - \nabla^2\right) w_z - S_h \frac{\partial^2 w}{\partial z^2} = 0, \tag{16}$$

$$\left(\frac{-1}{Pr}\frac{\partial}{\partial t}\nabla^2 + \nabla^4\right)\omega + R_T \nabla_h^2 T - R_n \nabla_h^2 \phi + S_h\left(\nabla_h^2 w_z - \frac{\partial^2}{\partial z^2} w_z\right) = 0. \tag{17}$$

Where $\quad w_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$

By removing w_z from equations (16) & (17) and considering equations (14),(15)

$$\left[\left(\frac{1}{Pr}\frac{\partial}{\partial t}\nabla^2 - \nabla^4\right)\left(\frac{1}{Pr}\frac{\partial}{\partial t} - \nabla^2\right) - S_h^2\frac{\partial^2}{\partial z^2}\left(\nabla_h^2 - \frac{\partial^2}{\partial z^2}\right)\right]\omega$$

$$-R_T\nabla_h^2\left(\frac{1}{Pr}\frac{\partial}{\partial t} - \nabla^2\right)T + R_n\nabla_h^2\left(\frac{1}{Pr}\frac{\partial}{\partial t} - \nabla^2\right)\phi = 0, \quad (18)$$

$$-\omega + \left(\frac{\partial}{\partial t} - \nabla^2\right)T = 0, \quad (19)$$

$$-\frac{N_A}{Le}\nabla^2 T + \left(\frac{\partial}{\partial t} - \frac{1}{Le}\nabla^2\right)\phi = 0. \quad (20)$$

Where $\nabla_h^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$, $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$.

Let us introduce the normal modes by writing the perturbations in the form of

$$(\omega, T, \phi) = (\omega, T, \phi)Sin(\pi z)e^{i(lx+my)+\sigma t}. \quad (21)$$

Substituting the above normal mode solution into the Eqs. (18)- (20), then we ge

$$\left[\left(\frac{\sigma}{Pr}\delta^2 + \delta^4\right)\left(\frac{\sigma}{Pr} + \delta^2\right) + S_h^2(\pi^2 q^2 - \pi^4)\right]\omega - R_T q^2\left(\frac{\sigma}{Pr} + \delta^2\right)T$$

$$+R_n q^2\left(\frac{\sigma}{Pr} + \delta^2\right)\phi = 0, \quad (22)$$

$$\omega - (\sigma + \delta^2)T = 0, \quad (23)$$

$$\frac{N_A}{Le}\delta^2 T + \left(\sigma + \frac{1}{Le}\delta^2\right)\phi = 0. \quad (24)$$

Where
$$\begin{cases} q^2 = l^2 + m^2 \ is\ the\ wave\ number, \\ \sigma = \iota\omega, \\ \delta^2 = \pi^2 + q^2. \end{cases}$$

Requiring zero determinant of the above system , one obtains,

$$R_T = -\frac{\delta^2 N_A R_n}{\delta^2 + Le\sigma} + \frac{(\delta^2+\sigma)(\delta^2(Pr\delta^2+\sigma)^2 + \pi^2 Pr^2(-\pi^2+q^2)S_h^2)}{Prq^2(Pr\delta^2+\sigma)}. \quad (25)$$

3.1 Stationary Convection

Substituting ω= 0 in Eq. (25), then we get

$$R_{T_{sc}} = \frac{\delta^6 - q^2 N_A R_n + \pi^2(-\pi^2+q^2)S_h^2}{q^2} \quad (26)$$

For Newtonian liquids, in the absence of helical force, the above formula becomes

$$R_{T_{sc}} = \frac{\delta^6}{q^2} \quad (27)$$

which is well agreed with Chandrasekhar [6].

3.2 Oscillatory Convection

To find the R_T for oscillatory convection we find the roots of imaginary part of Rayleigh number. On substituting roots into the real part of Rayleigh number we get the R_T for oscillatory convection.

$$R_{T_{oc}} = \frac{b_1+b_2\omega^2+b_3\omega^4+b_4\omega^6}{b_8+b_9\omega^2+b_{10}\omega^4} \tag{28}$$

Where

$$b_1 = Pr^3\delta^8 + (\delta^6 - q^2N_ARn + \pi^2(-\pi^2+q^2)Sh^2),$$

$$b_2 = Pr\delta^4((1+Pr(-1+Le^2Pr))\delta^6 - q^2N_ARn - \pi^2Pr(1+Le^2Pr)(\pi-q)(\pi+q)Sh^2)$$

$$b_3 = (-1-Le^2(-1+Pr)Pr)\delta^6 + Le^2\pi^2Pr^2(-\pi^2+q^2)Sh^2,$$

$$b_4 = -Le^2\delta^2,$$

$$b_8 = Pr^3q^2\delta^8,$$

$$b_9 = Pr(1+Le^2Pr^2)q^2\delta^4,$$

$$b_{10} = Le^2Prq^2.$$

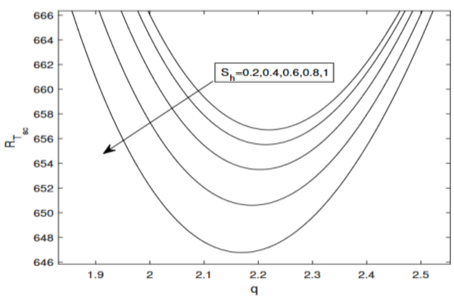
Where $\omega^2 = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$

$$a = Le^2(1+Pr)\delta^4$$

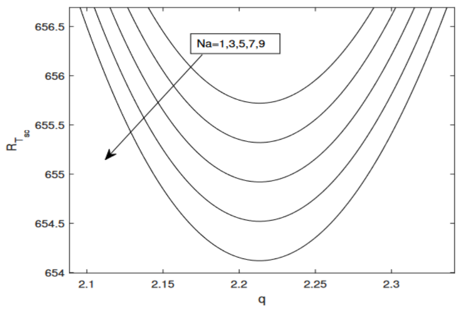
$$b = \delta^2((1+Pr)(1+Le^2Pr^2)\delta^6 + LePr(q^2N_ARn - Le|pi^2(-1+Pr)Pr(\pi-q)(\pi+q)Sh^2),$$

$$c = Pr^2\delta^6((1+Pr)\delta^6 + LePrq^2N_ARn - \pi^2(-1+Pr)(\pi-q)(\pi+q)Sh^2).$$

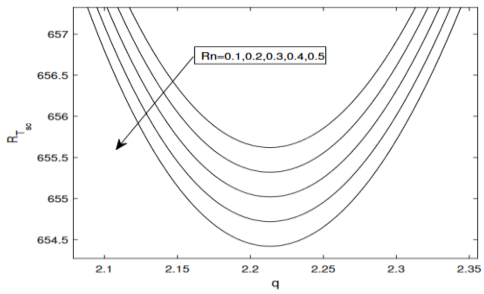
4. **Results**



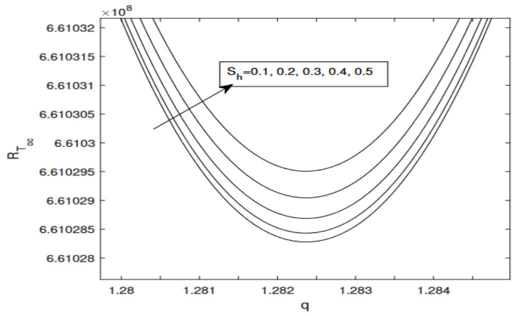
Neutral curves for the different values of S_h and for the fixed values of $N_A = 2, Pr = 5, Rn = 0.2, Le = 10$ at the onset of stationary convection.



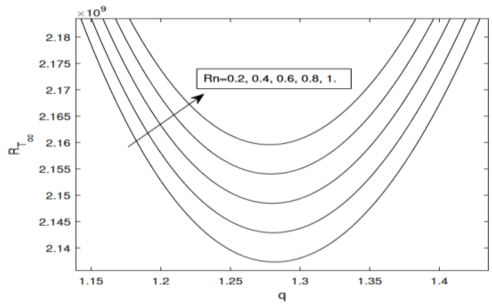
Neutral curves for the different values of N_A and for the fixed values of $S_h = 0.4, Pr = 3, Rn = 0.2, Le = 5$ at the onset of stationary convection.



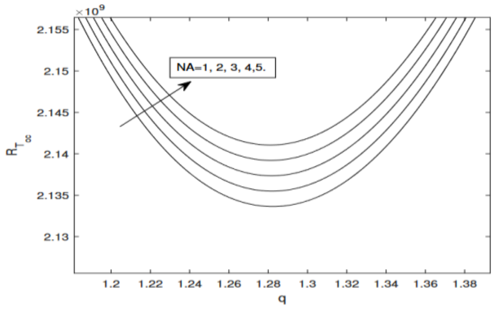
Neutral curves for the different values of Rn and for the fixed values of $N_A = 3, Pr = 3, S_h = 0.4, Le = 5$ at the onset of stationary convection.



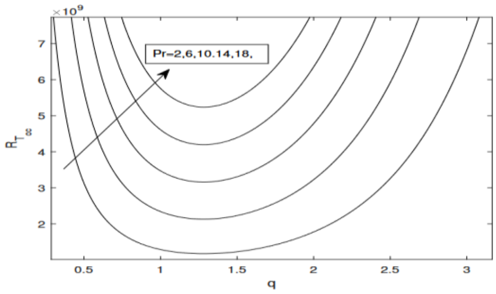
Neutral curves for the different values of S_h and for the fixed values of $N_A = 1, Pr = 2, Rn = 0.2, Le = 3$ at the onset of stationary convection.



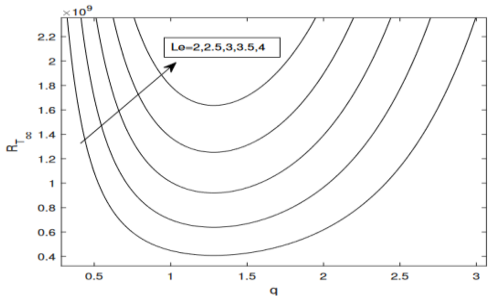
Neutral curves for the different values of Rn and for the fixed values of $N_A = 1, Pr = 6, S_h = 2, Le = 4$ at the onset of stationary convection.



Neutral curves for the different values of N_A and for the fixed values of $S_h = 2, Pr = 6, Rn = 0.2, Le = 4$ at the onset of stationary convection.



Neutral curves for the different values of Pr and for the fixed values of $N_A = 2, S_h = 1, Rn = 0.1, Le = 4$ at the onset of stationary convection.



Neutral curves for the different values of Le and for the fixed values of $N_A = 4, Pr = 5, Rn = 0.2, S_h = 2$ *at the onset of stationary convection.*

The influence of helical force on the convective instability of nanofluid is examined. As per our knowledge, the present problem has not been studied before. The non-dimension governing parameters of the onset of the convection are the Rayleigh number (R_T), Helical force (S_h), Lewis number (Le), Prandtl number (Pr), Modified diffusivity ratio (N_A), and Concentration Rayleigh number (Rn). The eigenvalue problem for linear stability analysis is solved by employing Galerkin approach which gives the analytical expression for Rayleigh number. Neutral curves are drawn for both stationary and oscillatory instability for all physical parameters.

Figs. 1-3 shows the neutral curves in the plane $\left(R_{T_{sc}}, q\right)$. Lewis number and Prandtl number does not show any effect on the neutral curves in the plane $\left(R_{T_{sc}}, q\right)$, because, $R_{T_{sc}}$ is independent of Pr and Le, which is clearly obtained equation [26].

Fig 1. shows that the neutral stability curves for the swap of stabilities in the parametric plane (q, R_T) with different values of Helical force S_h $(S_h = 0.2,0.4,0.6,0.8,1)$ and for the fixed values $N_A = 2, Rn = 0.2$ for each assignment the helical force S_h, N_A, and Rn a neutral stability curve presented. From this figure we can observe that the neutral stability curves move down-ward monotonically as S_h decrease, clearly indicating the instability in the system. In other words, decreasing value of S_h has destabilizing effect.

Figs. 2 and 3 respectively. According to these, as Na and Rn increases critical $R_{T_{sc}}$ decreases. Means that, N_A and Rn have destabilizing effect in the system. The neutral curves at the onset os oscillatory convection have shown in Figs.4-8 the distinct values of physics parameters. Fig 4. shows that the neutral stability curves for the swap of stabilities in the parametric plane (q, R_T) with different values of helical force S_h $(S_h = 0.1,0.2,0.3,0.4,0.5)$ and for the fixed values $N_A = 1, Rn = 0.2, Pr = 2,$ and $Le = 3$ for each assignment the helical force S_h, N_A, Pr, Le and Rn a neutral stability curve presented. It is observed that as S_h increases the neutral curves move upward monotonically and indicating that instability in the system.

Figs. 5 and 6 respectively. According to these, as N_A and Rn increases critical $R_{T_{oc}}$ increases. Means that,N_A and Rn have a stabilizing effect in the system. The opposite behaviour are N_A and Rn observed in stationary convection. Effect of Pr on $R_{T_{oc}}$ has shown in Fig. 7. Critical $R_{T_{sc}}$ increases as Pr decreases, then it is indicating that an enhance in the value of Pr advances the onset of oscillatory convection. In Fig. 8, neutral curves have been shown for distinct values of Le at the onset of oscillatory convection. It is shown that the critical $R_{T_{sc}}$ is a increasing function of Le. Hence, Le has stabilizing effect on the flow.

Stationary	Oscillatory			
	Pr	Le		
		0.1	1	5
608.1926	0.1	981.5832	2306489.739	1440920832.46
608.1926	1	7248.588542	65259254.04	1634978106.99
608.1926	2	25807.3735	73462961.68	1841074099.93
608.1926	3	70056.73	87075590.47	2183152754.30
608.1926	4	141701.8799	02047967.1	2559234616.27
608.1926	5	250288.4045	117564272.8	2948919993.18
608.1926	6	403396.5843	133352554.9	3345408006.27
608.1926	7	608606.7082	149296257.7	3745783622.03
608.1926	8	873500.3287	165337101.6	4148589189.27
608.1926	9	1205664.575	181442707.7	4553014837.94
608.1926	10	1612717.851	197593648.4	4958574607.91

Critical values of R_T steady and Oscillatory Convection are reported in table. We fix $N_A = 4$, $S_h = 2$ and $Rn = 0.2$. From this table, it is clear that Pr and Le does not show any effect on critical R_T for steady instability. And also, critical $R_{T_{sc}}$ is always less than critical $R_{T_{oc}}$. Hence, we can conclude that the Convection arises via Stationary Convection only.

4.1. Conclusions

This work considers the convective instability problem of a nanofluid with magnetic effects with linear evaluations. The Galerkin method is used to study the linear theory. Remarkably, there is no appreciable effect of the Prandtl number Pr and Lewis number Le on stationary convection. However, the Helical force $S_h$destabilize the flow whereas the, concentration Rayleigh number Rn and modified diffusivity ratio N_A destabilizes the flow. However, in oscillatory convection, it is discovered that the concentration Rayleigh number Rn, modified diffusivity ratio N_A, Lewis number Le and Prandtl Pr and Helical force $S_h$stabilize the flow.

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