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ARTICLE

Internal Heat Modulation on Darcy Convection in a Porous Media Saturated by Nanofluid

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In this paper we investigate the effect of internal heat modulation over a nanofluid saturated porous medium. We consider a small variation in time dependant heat source and vary sinusoidally with slow time. An energy equation will be altered by adding time dependant internal heat source. This internal heat source has its time dependent and independent parts. Time dependent part shows that the internal heat modulation over a porous media and defines controls on heat/mass transfer in the layer. We have performed a nonlinear stability analysis to investigate heat/mass transfer in the system. The nonlinear system of partial differential equations are transformed into nonlinear ordinary differential equations under similarity transforms up to the second term. This system has different system parameters and they have been investigated on heat and mass transfer graphically. The dual nature, stabilize or destabilize is due to the significant effect of internal heating modulation of the system. Further, the effect of internal heating is to destabilize the system, as a consequence heat/mass transfer enhances. It is found that internal heating modulation can be used effectively to regulate heat/mass transfer in the system.

KEYWORDS: Thermal Instability, Internal Heat Modulation, Internal Heating, Darcy Model, Nanofluids.

1. INTRODUCTION

In the case of nonlinear thermal instability the concept of stabilization or destabilization can be a challenge, for this many authors have done huge amount of research on stability theory. The advanced concepts of nanofluids offer absorbing heat transfer characteristics compared to conventional heat transfer fluids. On-going research indicates that it is possible when one consider base fluids (several liquids including water, ethylene glycol, and oils) along with nanoliquids can stabilize instability. There are many applications of nanofluids, nanofluid synthesis include metallic particles, oxide particles, carbon nanotubes, graphene nano-flakes and ceramic particles. Mainly in industries such as heat exchanging devices appear promising with these characteristics. Common fluids have limited heat transfer capabilities while some of the metals have very high thermal conductivity in comparison to these fluids. This is the reason better combinations of nanofluids and base fluids we can control stability analysis as well as heat/mass transfer rates.

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Nanofluids are mixtures of base fluid such as water or ethylene-glycol along with small amount of nanoparticles such as metallic or metallic oxide particles (Cu, Cuo, Al_2O_3), having dimensions from 1 to 100 nm. Masuda et al.[1] was examined that how much thermal conductivity of a liquid can be altered by dispersing a small amount of ultra-fine particles into base fluids. It is observed that for the systems of water-Al_2O_3 and water-TiO_2, the effective thermal conductivities were seen to increase much more as the particle concentration was increased, but the trend is reverse for water-SiO_2 system. Choi[2,3] was the first, who proposed this term nanofluid. He found that nanofluids exhibit high thermal conductivities compared to those of currently used heat transfer fluids, and they represent the best hope for enhancement of heat transfer. Natural convection is the heat removal strategy adopted in a wide variety of industries ranging from transportation (heating, ventilation, and air conditioning), energy production and supply to electronics, geophysical problems, textiles and paper production, nuclear reactors to name a few. Eastman et al.[4] reported that there is 40% increase of ethylene glycol thermal conductivity for nanofluids consisting of 0.3% volume of copper nanoparticles of 10 nm diameter. Further 10–30% increase of the effective thermal conductivity in alumina/water nanofluids with 1–4% of alumina was reported by Das et al.[5] Buongiorno[6] investigated boundary layer flow consisting of nanofluids. It was found that nanofluid properties may vary significantly within the boundary layer because of the effect of the temperature gradient and thermophoresis. Also these effects can result in a significant decrease of viscosity within the boundary layer, thus leading to heat transfer enhancement. Another application of the nanofluid flow is in the delivery of nano-drug as suggested by Kleinstreuer et al.[7] The relevant studies of various nanfluid flow models well documented by Kuznetsov and Nield,[8–10] Nield and Kuznetsov,[11–14] Krishna and Chamkha[15,16] and Dogonchi et al.[17,18]

The effect of local thermal non equilibrium on linear and nonlinear thermal instability in a horizontal nanofluid porous layer ws investigated by Bhaduria and Agarwal.[19,20] Agarwal and Bhaduria[21] and Agarwal and Bhaduria[22] studied thermal instability in a rotating porous layer saturated by a nanofluid for top and bottom-heavy suspension for Darcy model. The effect of various parameters on heat/mass transfer reported in detailed graphical model. Agarwal et al.[23] studied double diffusive convection in a horizontal porous layer saturated by a nanofluid, for the case where the base fluid of the nanofluid is itself a binary fluid such as salty water. Chand and Rana[24] investigated the onset of thermal convection in rotating nanofluid layer saturated porous medium. Boundary and internal heat source effects on the onset of Darcy-Brinkman convection in a porous layer saturated by nanofluid was analysed by Yadav et al.[25] No study in the above literature carried out modulation work. The study of unsteady mixed convection related problems in nanofluids has been presented in (Takhar et al.,[26] Chamkha et al.[27,28] without any modulation. The hall and ion slip effects on MHD rotating boundary layer flow of nanofluid past an infinite vertical plate embedded in a porous medium has been investigated by Krishna and Chamkha.[29] Hall effects on unsteady MHD oscillatory free convective flow of second grade fluid through porous medium between two vertical plates was given by Krishna et al.[30–31]).

The effect of entropy generation on nanofluid convection has been studied by Parvin and Chamkha[32] and Muneer et al.[33] The effect of throughflow on weakly nonlinear convection in a viscoelastic saturated porous medium was given by Kiran et al.[34] The effect of thermal radiation and shape factor of nanoparticles impacts on nanofluid natural convection in a cavity under was given by Chamkha et al.[35] Other related studies of nanofluid convection are presented in the following studies.[36–38] The studies related to double diffusive convection or heat mass transfer for different porous layers recently was given by Krishna et al.[39–41] and Eshaghi et al.[42] Venezian[43] performed thermal modulation on linear stability analysis of Rayleigh–Bénard convection with free boundary conditions. He determined the correction in critical Rayleigh number and declared that by suitably tuning the frequency of modulation one can regulate convective instability effectively. The critical Rayleigh number was evaluated as a function of wavenumber and frequency of modulation. Gresho and Sani[44] investigated a linearized stability analysis to show that gravity modulation can significantly affect the stability limits of the system. This concept of modulation is applied to control instability and transport theory of heat and mass.

The effect of thermal and gravity modulations on nanofluid convection are not available in the literature. There are vary few articles investigated effect of modulation on nanofluid convection. There are few simultaneous studies of modulation work on nanofluid convection. This modulation concept has not been applied to nanofluid convection. There are few studies available in the literature. Recently, Umavathi[45] studied both temperature and gravity modulation of convection in a porous medium saturated by a nanofluid by using a linear stability analysis. This motivated us to do a nonlinear analysis of thermal instability in a nanofluid saturated porous medium under gravity modulation as till date no nonlinear study is available on this aspect. Nonlinear thermal instability of a viscoelastic nanofluid saturated porous medium under gravity modulation has been investigated by Kiran.[46] The effect of internal heating and gravity modulation on thermal nanofluid convection saturated with porous medium investigated by Kiran et al.[47] The same problem has been extended for thermal modulation by Kiran and Narasimhulu[49] The study of centrifugally driven convection in a nanofluid saturated rotating porous medium with rotation speed modulation has been in- vestigated by Kiran and Narasimhulu[50] The effect of gravitational modulation effect on double-diffusive oscillatory convection in a viscoelastic fluid layer was given by Kiran.[51,52] The effect of gravity modulation on thermal instability using Landau mode recently investigated by Manjula et al.[53–57] Manjula et al.[55,56] has investigated the effect of gravity modulation on heat transport by a weakly nonlinear thermal instability in the presence of applied magnetic field and internal heating.

However, to the best of author's knowledge till date no study reports the effect of internal heat modulation on nanofluid convection. The literature shows nanofluid convection under thermal, gravity and rotation speed modulation but, till date no study investigated internal heat modulation on nanofluid convection. Therefore, the purpose of the present study is to see the effect of internal heat modulation on the nanofluid convection in a horizontal porous media and quantify heat and mass transfer.

2. PROBLEM FORMULATION

In this article we consider a porus layer of nanofluid confined between two parallel plates situated at $z = 0$ (lower plate) and $z = d$ (upper plate). These plates are departed at distance d vertically. The plates considered here are heated from below and cooling from above (see Fig. 1).

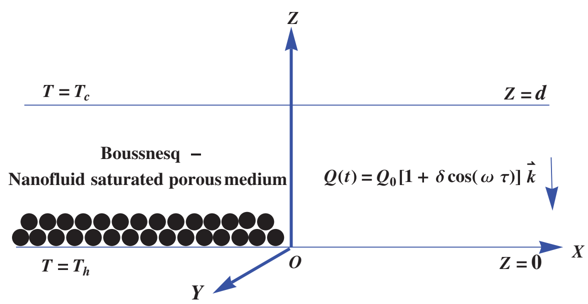

Fig. 1. Graphical representation of the problem.

The porous layer has been extended in x and y-directions infinitely and z-axis is taken vertically upward with the origin at lower plate. The local thermal equilibrium state has been considered between the fluid and solid. Thus, flow of heat rate is more at lower plate than the upper plate (in general $T_h > T_c$). Further, the Oberbeck-Boussinesq approximation has been employed for the modulation fluctuation in the porous media. The mathematical expression for the system of governing equations are given by (see Kiran,[46] Kiran et al.[47]):

$$\nabla\cdot\mathbf{q}_D = 0 \tag{1}$$

$$\frac{\rho f}{\varepsilon_p}\frac{\partial \mathbf{q}_D}{\partial \tau} = -\frac{\mu}{K}q_D - \nabla p + [\phi\rho_p + (1-\phi)\{\rho(1-\beta(T-T_c))\}]\vec{g} \tag{2}$$

$$\gamma\frac{\partial T}{\partial \tau} + \mathbf{q}_D\cdot\nabla T = \kappa_T\nabla^2 T + \varepsilon_p\frac{(\rho c)_p}{(\rho c)_f}\times\left[D_B\nabla\phi\cdot\nabla T + \frac{D_T}{T_c}\nabla T\cdot\nabla T\right] + \overrightarrow{Q(t)}(T-T_0) \tag{3}$$

$$\frac{\partial\phi}{\partial\tau} + \frac{1}{\varepsilon_p}q_D\cdot\nabla\phi = D_B\nabla^2\phi + \frac{D_T}{T_c}\nabla^2 T \tag{4}$$

$$\overrightarrow{Q(t)} = Q_0\left(1+\delta\cos(\omega\tau)\right)\vec{k} \tag{5}$$

Here the first equation is represents continuity equation and determines the continuum hypothesis. The second equation is of momentum equation including with Darcy term. Third equation is energy equation along with internal heating. The physical variables in the above system have their usual meanings presented at nomenclature. We consider the upper and lower plates are impermeable. We assume that, the temperature and the volumetric fraction of the nanoparticles are constant at the boundaries with thermal equilibrium (Kiran[46]). Thus, the boundary conditions are as (Kiran et al.[47–50]):

$$v = 0,\quad T = T_h,\quad \phi = \phi_0 \ \text{ at } \ z = 0 \tag{6}$$

$$v = 0,\quad T = T_c,\quad \phi = \phi_1 \ \text{ at } \ z = d \tag{7}$$

where nanoparticle concentration ϕ_1 at upper plate is greater than nanoparticle concentration ϕ_0 at lower plate. The dimensionless variables are considered as given below:$(x^*, y^*, z^*) = (x, y, z)/d$, $\tau^* = \tau\kappa_T/\gamma d^2$, $(u^*, v^*, w^*) = (u, v, w)d/\kappa_T$, $p^* = pK/\mu\kappa_T$, $\phi^* = (\phi-\phi_0)/(\phi_1-\phi_0)$ and $T^* = (T-T_c)/(T_h-T_c)$, where $\kappa_T = k_m/(\rho c)_f$, $\gamma = (\rho c_p)_m/(\rho c_p)_f$. The non-dimensionalized governing equations along with boundary conditions are (after dropping the asterisk for simplicity)

$$\nabla\cdot q = 0 \tag{8}$$

$$\frac{1}{Va}\frac{\partial q}{\partial\tau} = -\nabla p - q - (Rm - RaT + Rn\phi)\,\hat{e}_z \tag{9}$$

$$\frac{\partial T}{\partial\tau} + q\cdot\nabla T = \frac{N_A N_B}{Le}\nabla T\cdot\nabla T + \left(\nabla^2 + R_i f(\Omega, t)\right)T + \frac{N_B}{Le}\nabla\phi\cdot\nabla T \tag{10}$$

$$\gamma^{-1}\frac{\partial\phi}{\partial\tau} + \varepsilon_p{}^{-1}q\cdot\nabla\phi = \frac{1}{Le}\nabla^2\phi + N_A Le^{-1}\nabla^2 T \tag{11}$$

$$q = 0,\quad T = 1,\quad \phi = 0 \quad \text{at} \quad z = 0,$$
$$\text{and}\quad q = 0,\quad T = 0,\quad \phi = 1 \quad \text{at} \quad z = 1 \tag{12}$$

where $f(\Omega, t) = (1 + \epsilon^2\delta\cos(\Omega t))$. The dimension less parameters in the above equations are given in nomenclature.

2.1. Conduction State

At this state heat and mass transfer are in the form of conduction only. In general initial state of convection there will be a instability near the boundary of the plate. So the heat and mass transfer are taking place near the plate in the form of conduction only. Before heat mass transfer takes place in the fluid, this state is accumulated with basic state quantities in z-direction which are given by (see Kiran et al.[46,47] and Bhadauria and Agarwal[19,20]):

$$q = 0,\quad p = p_b(z),\quad T = T_b(z),\quad \phi = \phi_b(z) \tag{13}$$

Substituting the Eq. (13) in Eqs. (10) and (11), and simplifying we obtain the following equation:

$$\frac{d^2T_b}{dz^2} + R_i T_b + \frac{N_B}{Le}\frac{d\phi_b}{dz}\frac{dT_b}{dz} + \frac{N_A N_B}{Le}\left(\frac{dT_b}{dz}\right)^2 = 0 \tag{14}$$

Within the magnitude analysis (see Chand and Rana[24] and Kiran et al.[46,47] we assume that the second and third terms in Eq. (14) are small, and then we have:

$$\frac{d^2T_b}{dz^2} + R_i T_b = 0,\qquad \frac{d^2\phi_b}{dz^2} = 0 \tag{15}$$

The usual boundary conditions to solve Eq. (15) may obtained from Eq. (12) are (see Bhadauria and Agarwal,[19,20] Kiran et al.[46,47]):

$$T_b = 1, \quad \phi_b = 0 \quad \text{at} \quad z = 0 \tag{16}$$

$$T_b = 0, \quad \phi_b = 1 \quad \text{at} \quad z = 1 \tag{17}$$

We solve the Eq. (15), subject to the above boundary conditions Eqs. (16) and (17), we get the dimension less basic temperature:

$$T_b = \frac{\sin\sqrt{R_i}\,(1-z)}{\sin\sqrt{R_i}} \tag{18}$$

$$\phi_b = z \tag{19}$$

where R_i is the internal rayleigh number determines heat source and heat sink. The reader may observe that the values of R_i are positive for heat source and negative for heat sink. In order to avoid the dominant nature of R_i we consider here the moderate values of R_i.

2.2. Perturbed State

We observe in this state that once the conduction regime gets over (i.e., convection takes place) there will be a significant disturbances in physical quantizes. So we now consider the superimpose perturbations to the conduction state given in Eq. (13): (for reference see Bhadauria and Agarwal[19,20] and Kiran and Narasimhulu[49,50]

$$q = q', \quad p = p_b + p', \quad T = T_b + T', \quad \phi = \phi_b + \phi \tag{20}$$

Now we substitute the above expression (20) in Eqs. (8)–(11) and using the expressions (18) and (19), we get the following system of equations while eliminating the pressure term and introducing the stream functions:

$$\frac{1}{Va}\frac{\partial}{\partial \tau}\left(\nabla^2\psi\right) + \nabla^2\psi = \left(Rn\frac{\partial \phi}{\partial x} - Ra\frac{\partial T}{\partial x}\right)\vec{k} \tag{21}$$

$$-\frac{\partial T_b}{\partial z}\frac{\partial \psi}{\partial x} - \left(\nabla^2 + R_i f(\Omega, t)\right)T = -\frac{\partial T}{\partial \tau} + J(\psi, T) \tag{22}$$

$$-\frac{1}{\varepsilon_p}\frac{\partial \psi}{\partial x} - \frac{N_A}{Le}\nabla^2 T = \frac{1}{Le}\nabla^2\phi - \frac{1}{\gamma}\frac{\partial \phi}{\partial \tau} + \frac{1}{\varepsilon_p}J(\psi, \phi) \tag{23}$$

where J represents Jacobin.

The Jacobian term which are in Eqs. (22)–(23) are given by: $J(\psi, T) = (\partial\psi/\partial x)(\partial T/\partial z) - (\partial\psi/\partial z)(\partial T/\partial x)$, $J(\psi, \phi) = (\partial\psi/\partial x)(\partial\phi/\partial z) - (\partial\psi/\partial z)(\partial\phi/\partial x)$. It is observed that Eq. (22) the term $\left(\nabla^2 + R_i f(\Omega, t)\right)$ determines the effect of internal heat modulation. The reader may observe few studies on internal heating without modulation given by Yadav et al.,[25] Kiran.[46]

3. NONLINEARITY

For nonlinear system we consider the Fourier series expressions for the physical variables such as stream function, temperature and nanoparticle fraction, a local nonlinear stability analysis is performed. We consider the modes (1,1) for stream function, and (0,2) and (1,1) for temperature and nanoparticle. It is noted that the effect of nonlinearity is to distort the temperature and concentration fields through the interaction of ψ, T, ψ and ϕ respectively. As a result a component of the form $\sin(2\pi z)$ will be generated for the interaction of the flow. Therefore, the minimal expression which describes the finite amplitude convection is obtained by.

$$\psi = A_{11}(\tau)\sin(\alpha x)\sin(\pi z) \tag{24}$$

$$T = B_{11}(\tau)\cos(\alpha x)\sin(\pi z) + B_{02}(\tau)\sin(2\pi z) \tag{25}$$

$$\phi = C_{11}(\tau)\cos(\alpha x)\sin(\pi z) + C_{02}(\tau)\sin(2\pi z) \tag{26}$$

Here therm $A_{11}(\tau)$, $B_{11}(\tau)$, $B_{02}(\tau)$, $C_{11}(\tau)$ and $C_{02}(\tau)$ are unknown amplitudes needs to be determined. Using the Eqs. (24)–(26) in (21)–(23), and taking the orthogonality condition and associated with the considered minimal mode the following system we obtain.

$$\frac{dA_{11}(\tau)}{d\tau} = Va\delta^{2-1}\left[\alpha\left[RnC_{11}(\tau) - RaB_{11}(\tau)\right]\right.$$
$$\left. - \delta^2 A_{11}(\tau)\right] \tag{27}$$

$$\frac{dB_{11}(\tau)}{d\tau} = -\left[\frac{4\pi^2 a}{(4\pi^2 - R_i f(\Omega, t))}A_{11}(\tau) + \left(\delta^2 - R_i\right)\right.$$
$$\left. \times B_{11}(\tau) + \pi\alpha A_{11}(\tau)B_{02}(\tau)\right] \tag{28}$$

$$\frac{dB_{02}(\tau)}{d\tau} = \frac{\pi\alpha}{2}A_{11}(\tau)B_{11}(\tau)$$
$$- \left(4\pi^2 - R_i f(\Omega, t)\right)B_{02}(\tau) \tag{29}$$

$$\gamma^{-1}\frac{dC_{11}(\tau)}{d\tau} = -\left[\frac{\alpha}{\varepsilon_p}A_{11}(\tau) + \frac{1}{Le}\delta^2 C_{11}(\tau)\right.$$
$$\left. + \frac{\pi\alpha}{\varepsilon_p}A_{11}(\tau)C_{02}(\tau) + \frac{N_A}{Le}\delta^2 B_{11}(\tau)\right] \tag{30}$$

$$\gamma^{-1}\frac{dC_{02}(\tau)}{d\tau} = \frac{\pi\alpha}{2\varepsilon_p}A_{11}(\tau) - \frac{4\pi^2}{Le}\left[C_{02}(\tau) + N_A B_{02}(\tau)\right] \tag{31}$$

The present system of simultaneous nonlinear ordinary differential equations can be subsequently solved numerically using Mathematica NDSolve.

4. TRANSPORT PHENOMENON

The thermal Nusselt number, Nu(τ) is defined as

$$Nu(\tau) = \frac{\text{Heat transport by (conduction + convection)}}{\text{Heat transport by conduction}}$$

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$$= 1 + \left[\int_0^{2\pi/\alpha_c} \left(\frac{\partial T}{\partial z} \right) dx \Big/ \int_0^{2\pi/\alpha_c} \left(\frac{\partial T_b}{\partial z} \right) dx \right]_{z=0} \tag{32}$$

Substituting Eqs. (18) and (25) in Eq. (32), we get

$$Nu(\tau) = 1 - 2\pi B_{02}(\tau) \tag{33}$$

The nanoparticle concentration Nusselt number, $Nu_\phi(\tau)$ is defined similar to the thermal Nusselt number.

$$Nu_\phi(\tau) = (1 - 2\pi C_{02}(\tau)) + N_A(1 - 2\pi B_{02}(\tau)) \tag{34}$$

In Eqs. (33) and (34) 1 represents heat and concentration transport in conduction state.

5. DISCUSSIONS

The effect of internal heat modulation on nanofluid porous convection has been investigated. Nanofluids have been primarily used for their enhanced thermal conductivity properties as coolants in heat transfer equipment. They are heat exchangers, electronic cooling system and radiators. Heat transfer over flat plate (Rayleigh Benard problem) has been analyzed by many researchers. However, they are also useful for their controlled properties of heat mass transfer and instability. Nanofluids play a key role in heat and mass transfer due to their high thermal conductivity nature. These fluids are pioneered based on the properties of the fluids which are density, thermal conductivity, specific heat, and viscosity, along with system parameters such as diameter and length, modulation parameters and average fluid velocity. Therefore, it is important to measure the heat transfer performance of nanofluids in the media. One way preserving the regulation of heat and mass transfer is very much essential in the steady of thermal instability. Also increasing the effect of thermal conductivity is important in improving the heat mass transfer behavior of fluids. With this concept the present paper has been constructed to investigate such a parameters which control heat mass transfer in the media. Especially the effect of heat modulation and internal heating on heat and mass transport of the media has given importance. Therefore, it is very important to measure heat/mass transfer directly or indirectly under certain flow conditions.

It is well know that the nanofluids have an enhanced magnitude of thermal conductivity than normal fluids. The normal fluids or base fluids are converted nanofluids by suspending nano particles (Choi[2,3]). The nanofluids are combinations of base fluids with nano sized particles or fibers, suspended in them. It has been experimentally verified by many researchers in the past one decade. Here we have investigated the effect of internal heat modulation in a horizontal porous layer saturated by a nanofluid. Using the Brinkman model and considering top heavy porus layer, we performed a nonlinear stability analysis. A linear theory has been investigated by Umavathi,[45] Kiran et al.[47] concerning gravity modulation. It is well known fact that, nonlinear theory provides heat mass transport, which is not possible by linear theory. Moreover, external regulations of convection is very important to study thermal instability, therefore, this paper constructed for internal heat modulation for either enhancing or inhibiting heat/mass transport. Buongiorno[6] state that, most of the nanofluids have been investigated so far while choosing Le is large, but as per Bhaduria and Agarwal (2011), we have considered $Le = 15$ in the case of nanopartical concentration Rayleigh number. The effect of internal heat modulation on heat transport has been depicted in Figures 2–8. The following parameters Va, Rn, N_A, Le, γ, δ and ω occurring in the present study and influence the convective heat/mass transport.

The first five parameters are related to the porous layer and the next two parameters related to heat modulation. Due to small amplitude of modulation, the values of δ are considered to be small. Further, heat modulation assumed to be of low frequency, the effect of low frequency provides maximum heat/mass transport. The coefficient of heat/mass transport, i.e., thermal Nusselt number and concentration Nusselt number are calculated as function of system parameters. We have drawn the present results in the Figures 2–8 for $Nu(\tau)$ and $Nu_\phi(\tau)$ versus time τ. In the figures the values of $Nu(\tau)$ and $Nu_\phi(\tau)$ start with 1 and 2 showing convection is in progress. For later time it remains constant showing the conduction state. Then the values of $Nu(\tau)$ and $Nu_\phi(\tau)$ increase as time passes, thus showing convection is taking place. These values oscillate and then approach constant values further in time. This shows that a steady state has been achieved.

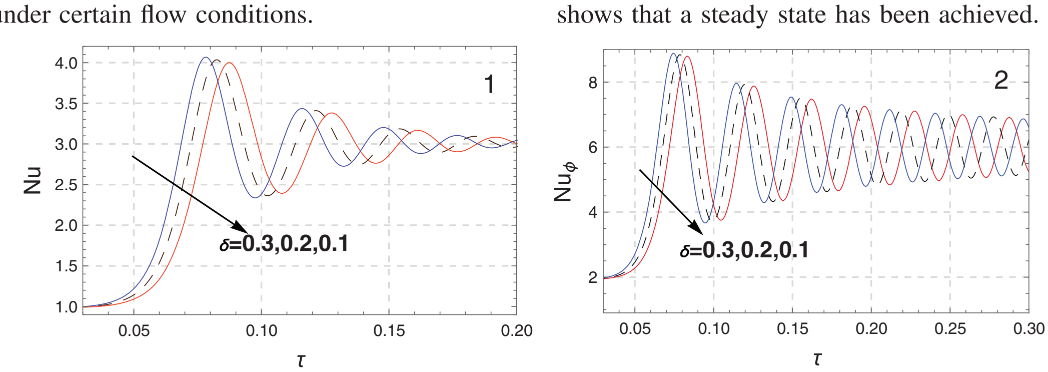

Fig. 2. Effect of amplitude of modulation on Nu and Nu_ϕ.

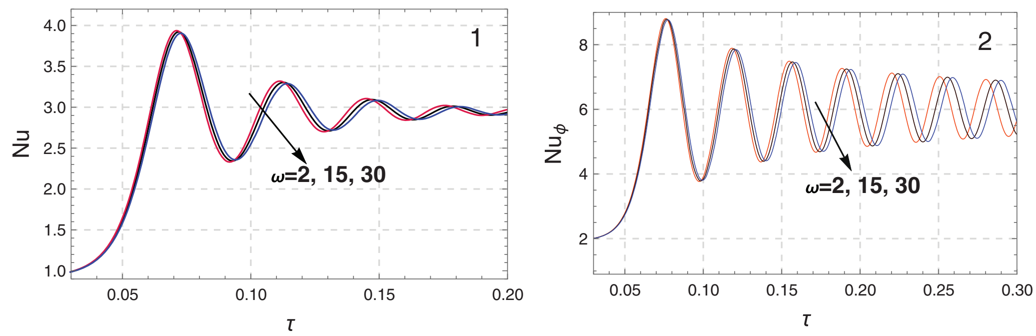

Fig. 3. Effect of frequency of modulation on Nu and Nu_{ϕ}.

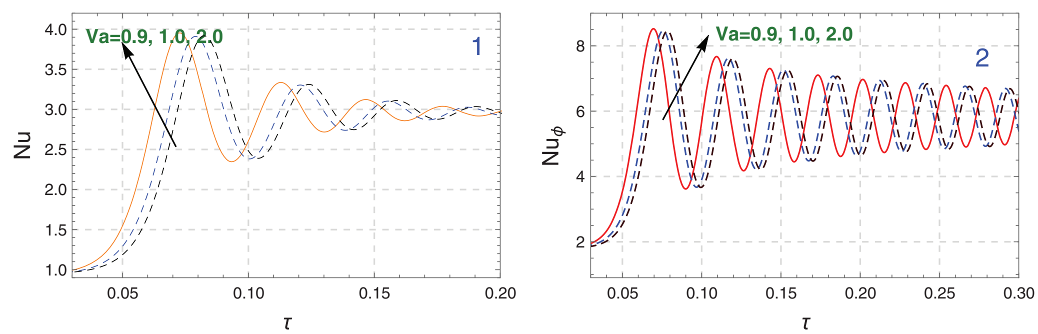

Fig. 4. Effect of Vadasz number on Nu and Nu_{ϕ}.

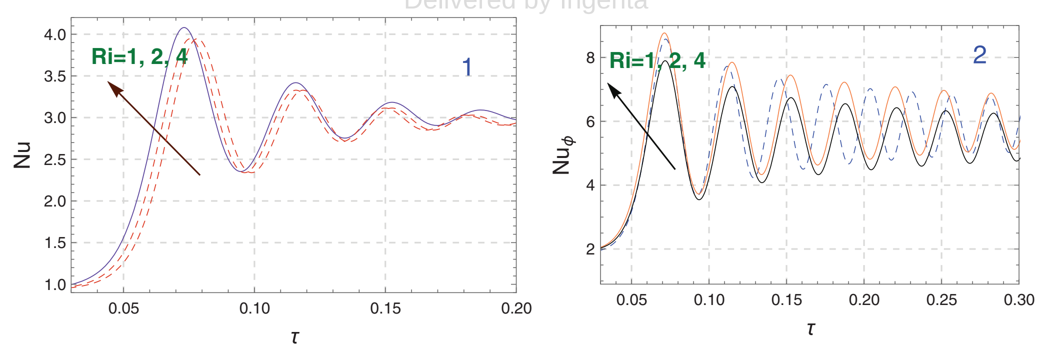

Fig. 5. Effect of internal Rayleigh number on Nu and Nu_{ϕ}.

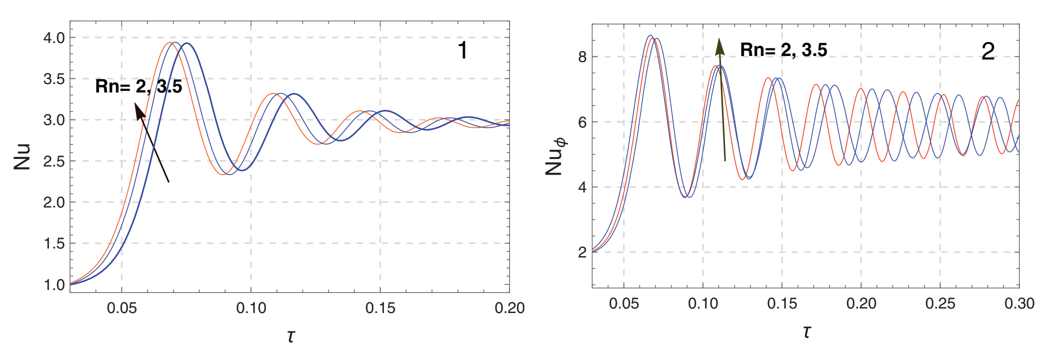

Fig. 6. Effect of internal concentration Rayleigh number on Nu and Nu_{ϕ}.

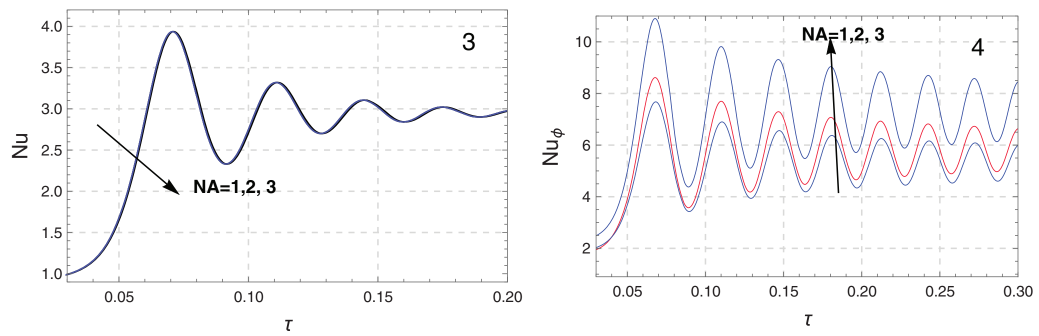

Fig. 7. Effect of NA on Nu and Nu_ϕ.

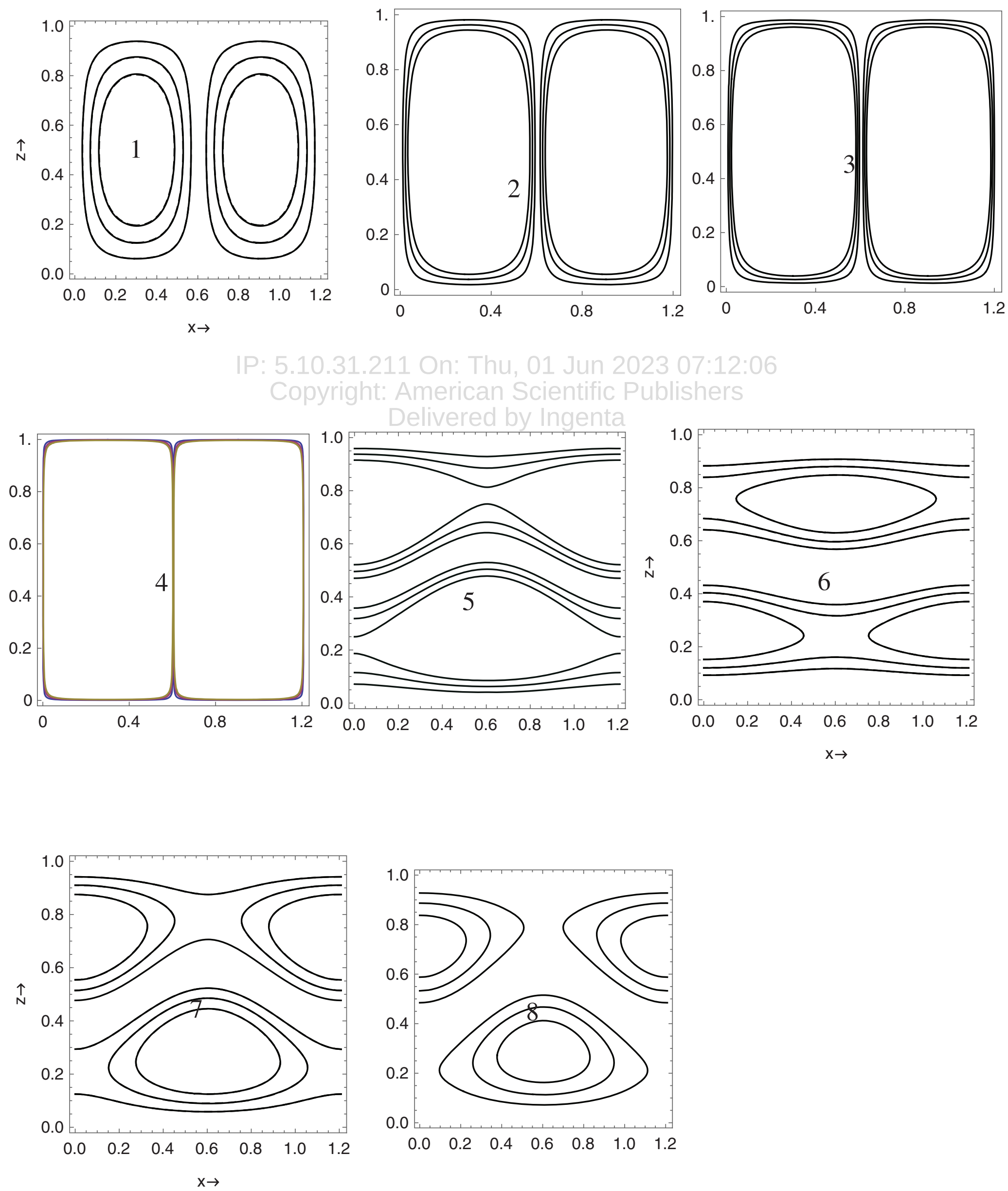

Fig. 8. Streamlines and isotherms for different values of τ ($\tau = 0.5$, 1.5, 2.5 & 4.0).

Now we will discuss the results related to the parameters of the problem. Figures 2(1) and (2), shows that the effect of amplitude of modulation enhances heat and nanoparticle concentration transport. The reader may observe respective variations by the graphical interpretation of Nu and Nu_{ϕ} given in Figures 2 and 3. The amplitude variations can be observed clearly from the Figures 2(1) and (2). These are the results are comparable with the results obtained by Kiran,[46,51] Kiran et al.[47,49,52] for different modulations. Here the value of δ is considered between 0 and 1 for low amplitude modulation. The effect of frequency of internal heat modulation has been presented in Figures 3(1) and (2). Figures 3(1) and (2) it is observed that upon increasing the frequency of modulation, heat and nanoparticle concentration transport is to decrease the values of Nu and Nu_{ϕ}, and hence stabilize the system. So this modulation effect can be applied to a system to control transport phenomenon. These results are comparable with the studies of Kiran,[46] Kiran et al.[47,50] for nanofluids. The reader may observe our previous studies (by Manjula et al.[53–57]) shows the effect of gravity modulation in terms of modulation amplitude and frequency on heat transfer which are having quite similar results.

We have presented the results corresponding to Vadasz number on Nu and Nu_{ϕ} in Figures 4(1) and (2). In general Va governs the effect of porosity on flow in a porous media. In fluid flow of fluid layer it is treated as Prandtl number Pr. In porous case it measures the rate of flow through porous layer. Its effect has presented in the Figure 4. From the Figures 4(1) and (2), we see that initially there is no variation in Nu and Nu_{ϕ}. For later there is enhancement in Nu and Nu_{ϕ} as the value of Prantdl-Darcy number Va increases. Thus, show that heat and concentration transport increases when Va increases. But for large values of time τ, the disturbances become small and subsequently the values of Nu and Nu_{ϕ} approach steady state. The reader may observe that the value of Va can be taken more than one, in that case the effect of local acceleration term will not counted in the problem. For large values of Va, one can see that there is increment in Nu and Nu_{ϕ}. For references related to Va, the reader may observe few studies which are given by Agarwal et al.,[22,23] Yadav et al.[25] and Kiran and Narasimhulu.[49]

However, the effect of thermal capacity ratio γ is to increase the value of Nusselt and concentration Nusselt numbers decrease, thus decreasing the rate of heat and concentration transport. The related figure is not included due to repetition. The effect of internal Rayleigh number R_i on Nu and Nu_{ϕ}, is presented in the Figures 5(1) and (2). Figures shows that Ri enhances heat and concentration transport in the layer for $Ri = 1$, 2 and 3. The reader may note that moderate values of Ri has consider in the layer to have control on the problem. The similar nature of Va and Ri was given by Kiran et al.[47] and Manjula et al.[53] Dissection of entropy production for the free convection of NEPCMs-filled porous wavy enclosure subject to volumetric heat source/sink was given by Afshar et al.[48]

We see that the influence of concentration Rayleigh number Rn on both thermal Nusselt number and concentration Nusselt number. It is found that Rn enhance heat and concentration transport as given in Figures 6(1) and (2), which is due to the fact that the nanoparticle concentration is more at the top. In general Rn is ration of nano-particle viscous force (due to bouncy) to the thermal diffusivity and fluid viscosity. Based on the nature of μ and κ_T, corresponding to the nanofluid there will be enhancement in heat and concentration transport. The reader may compare our results with Agarwal et al.[21–23] In Figure 7 we present the results of N_A and Le, these parameters do not have significant effect on the Nusselt number as reported earlier by Bhadauria and Agarwal[19] and Kiran et al.[47,49] Other side the effect of Le and N_A have increasing effect on Nu_{ϕ}, given in the Figures 7(1) and (2), and so the heat and concentration transport increases. Further, it is observed that the parameters Va, Rn, δ have destabilizing effect, while γ, ω have stabilizing effect. The parameters N_A, Le do not affect on Nu, but show significant effect on Nu_{ϕ}.

In Figures 8(2)–(8) we have depicted streamlines and isotherms to see the nature of convective phenomenon. As slow time varies from $\tau = 0.5$ to $\tau = 4$ there is significant effect of convection can be observed. The time-dependent terms of ψ (streamlines), T (isotherms), as a function slow time we have drawn the figures. Here we are not presenting the results of ϕ (isohalines), at different times due to repetition. It is clear that with increasing in time, magnitudes of streamlines, and isotherms are varying from their initial state (8(1), 8(2), 8(5), 8(6)). In streamlines one can observe enhancement in cell size, similarly in the case of isotherms, isotherms are more vibrant as time goes on. In all the Figures 8(3,4) to (7,8) there will be a rigorous change in streamlines and isotherms. In the case of isotherms, at initial state convection in the form of conduction which approaches to convection later state. The magnitude of isotherms increasing with slow time and achieves its unchangeble state after $\tau = 4$. It is quite natural to see the nature of streamlines and isotherms for Benard convection. The same results we obtained for the current problem. Our results are quite agree with the results obtained previously by Kiran et al.,[46,33] Kiran et al.[47] and Manjula et al.[53–57] In the intermediate time range, uniform convection cells are observed which change to strong convection with the passage of time.

6. CONCLUSIONS

We have investigated the effect of internal heating modulation on Darcy convection in a horizontal porous layer saturated by nanofluid. Based on the previous analysis we have drawn the following conclusions. The effect of modulation has dual role on heat and mass transport. It is

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found that low frequency of modulation shows destabilize effect but, high frequency modulation stabilize the system for Va and γ. The effect of internal heating is to increase (destabilizes) the heat transport as well as nanoparticle concentration transport. Increment in concentration Rayleigh number Rn, modified diffusivity ratio N_A and Lewis number Le increases the effect of heat modulation. An increment in Vadasz number enhances heat and concentration transport. It is found that no significant effect of N_A and Le on heat transport. Further, it is also found that Le, E, N_A and Rn is to enhance concentration transport, whereas Ω decreases the concentration transport. Finally the modulation can be used to regulate transport phenomenon in the system.

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NOMENCLATURE

Latin symbols		Unit
D_B	Brownian diffusion coefficient	m^2/sec
D_T	Thermophoretic diffusion coefficient	m^2/sec
Da	Darcy number, $Da = \frac{\bar{\mu}K}{\mu d^2}$	
q_D	Darcy velocity	m/sec
d	Dimensional layer depth	m
R_i	Internal Rayleigh number, $R_i = \frac{Qd^2}{\kappa_T}$	
Rm	Basic density Rayleigh number, $Rm = \frac{[\rho_p\phi_0 + \rho(1-\phi_0)]_{g0}Kd}{\mu\kappa_T}$	
Rn	Concentration Rayleigh number, $Rn = \frac{(\rho_p - \rho)(\phi_1 - \phi_0)_{g0}Kd}{\mu\kappa_T}$	
Le	Lewis number, $Le = \frac{\kappa_T}{D_B}$	
(x^*, y^*, z^*)	Cartesian coordinates	m
N_A	Modified diffusivity ratio $N_A = \frac{D_T(T_h - T_c)}{D_B T_c(\phi_1 - \phi_0)}$	
N_B	Modified particle-density increment, $N_B = \frac{(\rho c)_p(\phi_1 - \phi_0)}{(\rho c)_f}$	
$\vec{g}$	Modulated gravity field	m/sec^2
$\mathbf{q}$	Nanofluid velocity	m/sec

Latin symbols		Unit
K	Permeability of porous medium	m^2
Ra	Thermal Rayleigh-Darcy number, $Ra = \frac{\rho g_0 \beta K d(T_h - T_c)}{\mu\kappa_T}$	
p	Pressure	kg/(m sec^2)
T	Temperature	K
T_h	Temperature at the lower wall	K
T_c	Temperature at the upper wall	K
k_m	Thermal conductivity of porous medium	W/mK
τ	Time	sec
Va	Vadász number, $Va = \varepsilon_p Pr/Da$	

Greek Symbols

Latin symbols		Unit
ε	Amplitude of modulation	m
$(\rho c)_m$	Effective heat capacity of the porous medium	J/kgK
$(\rho c)_p$	Effective heat capacity of the nanoparticle material	J/kgK
$\bar{\mu}$	Effective viscosity of the porous medium	mPa s
ρ_f	Fluid density	kg/m^3
Ω	Frequency of modulation	sec^{-1}
$(\rho c)_f$	Heat capacity of the fluid	J/kgK
α	Horizontal wave number	
ρ_p	Nanoparticle mass density	kg/m^3
ε_p	Porosity	
β	Proportionality factor	K^{-1}
μ	Viscosity of the fluid	mPa sec
κ_T	Effective thermal diffusivity of the fluid	m^2/sec
γ	Heat capacity ratio $\frac{(\rho c)_m}{(\rho c)_f}$	
ν	Kinematic viscosity μ/ρ_f	m^4Pa sec/kg
ϕ	Nanoparticle volume fraction	
ψ	Stream function	m^2/sec

Subscripts

b Basic

Superscripts

$*$ Dimensional variable

' Perturbation variable

Operators

$$\nabla^2 \quad \frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$$

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