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A WEAKLY NON LINEAR STABILITY ANALYSIS OF HEAT TRANSPORT IN ANISOTROPIC POROUS CAVITY UNDER G-JITTER

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ABSTRACT

In this paper, we have analyzed the effect of time periodic gravity modulation i.e. G-jitter on convective instability in anisotropic porous cavity. The cavity is heated from below and cooled from above. The amplitude of gravity modulation is considered to be very small. A weakly nonlinear stability analysis is done to find Nusselt number governing the heat transport. Analytically the non-autonomous Ginzburg- landau amplitude equation is obtained for the stationary mode of convection. The effects of various parameters like Vadasz number, Mechanical and Thermal anisotropic parameters, Amplitude of oscillation, Frequency of modulation and Aspect ratio of cavity on heat transport is studied. It is observed that the heat transport can also be controlled by suitably adjusting the external and internal parameters of the system.

Keywords: *gravity modulation, anisotropic porous cavity, Ginzburg- landau amplitude equation.*

NOMENCLATURE

Latin Symbols			Greek symbols	
Ar	the aspect ratio of the porous cavity, H/L		ρ	Density
Va	Vadasz number		α_T	coefficient of thermal expansion
H	the height of cavity		ψ	stream function
K	permeability of the porous domain		μ	dynamic viscosity
L	the length of porous layer		ν	kinematic viscosity, μ/ρ_0
ΔT	temperature difference between the walls		ε	Porosity
p	Pressure		η	thermal anisotropic parameter
Nu	Nusselt number		ξ	Mechanical anisotropic parameter
Ra_0	Critical Rayleigh number		δ_1	amplitude of gravity modulation
g_0	mean gravity		ω	frequency of modulation
g	gravitational acceleration, $(0,0,-g)$		k	thermal diffusivity
Pr	Prandtl number, ν_*/κ_*		**Other symbols**	
q	velocity of the fluid (u, v, w)		c	critical state
Ra	Rayleigh number, $\frac{\alpha_{T*}(\Delta T) g_* H_* K_* M_f}{\varepsilon \nu_* \kappa_*}$		0	basic state
t	Time		,	perturbed state
T	Temperature		$*$	non-dimensional value
M_f	a ratio between the heat capacity of the fluid and the effective heat capacity of the porous domain		st	Stationary

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1. INTRODUCTION

Study of thermal instability in fluid layer in presence of complex body forces has gained considerable interest in recent time. One of the complex forces is time dependent gravitational field which is useful in space laboratory, crystal growth and large scale convection in atmosphere. Mechanical vibrations are useful to improve heat transport rate. Applications of gravity modulation in science and technology are geophysics, oil reservoir process, petroleum industry and solidification of polymeric liquids.

Gresho and Sani[16] was the first to study the effect of gravity modulation of a heated fluid layer. Gershuni *et. al.* [13] studied convective instability in presence of periodically varying parameter. Biringen and Peltier [7] studied the numerical simulation of 3D Bernard convection with gravity modulation and confirmed the results of Gresho and Sani. Clever *et. al.* [9-10] investigated a 3D as well as 2D oscillatory convection in a gravitationally modulated fluid layer for wider range of parameters. Yang [29] studied the stability of viscoelastic fluids in a modulated gravitational field. Vadasz [27] studied Coriolis Effect on gravity driven convection in a rotating porous layer heated from below. Vanishree[28] investigated combined effect of temperature and gravity modulation on the onset of convection in an anisotropic porous medium. Shu. *et.al.* [24] gave the comparison of experimental and numerical simulation for natural convection in a cavity under modulated thermal gradients and gravity. They concluded that modulation under gravity and temperature generates the same effects on convection. Aniss *et.al.* [1-2], Bhadauria [5] *et. al.* also studied the gravitational modulation under different regimes. They showed that the gravity modulation can be observed by vertically oscillating a horizontal fluid layer. It may have stabilizing or destabilizing effect. Boulal *et. al.*[8] studied the effect of quasi periodic gravitational modulation on the stability of a heated fluid layer and found that threshold of convection corresponds precisely to quasi periodic solutions. Siddheshwar *et. al.* [25] investigated the heat transport by stationary magneto convection in a Newtonian liquid under temperature or gravity modulation using Ginz-burg model and concluded that it may alter the heat transport. Bhadauria *et. al.* [6] studied the heat transport in a porous medium under G-jitter and internal heating effect and found that convective system destabilizes with respect to internal Rayleigh number. They found that the heat transport can be controlled by properly adjusting various parameters.

Anisotropy in porous media is generated due to asymmetric geometry of porous matrix. The phenomenon is observed in industry and nature. It is useful in study of extraction of metals from ores where a mushy layer is formed during solidification of alloys. The quantity and structure of resulting solid can be controlled by influencing the transport process. Process such as sedimentation, compaction, frost action and reorientation of the solid matrix are responsible for creation of anisotropic natural porous medium. Fiber materials and insulating materials are some examples of artificial anisotropic porous medium. Ephere [12] was the first to study the onset of convection in a horizontal porous layer with anisotropic thermal conductivity. Kvernvold *et. al.*[18] studied the non linear thermal convection in anisotropic porous media. Other researchers who studied thermal convection in anisotropic porous medium are Nilsen [23], Tyvand [26], Degan [11], Govinder [14-15], Malashetty *et. al.* [20-21]. Neild and Bejan [22] presented an excellent review for Convection in Porous Media. Bhadauria *et. al.* [4-3] studied Natural convection in a rotating anisotropic porous layer with internal heat generation and Double diffusive convection in a saturated anisotropic porous layer with internal heat source.

In this paper, we have investigated the effect of time periodic gravity modulation i.e. G-jitter on convective instability in anisotropic porous cavity. The cavity is heated from below and cooled from above. The amplitude of gravity modulation is considered to be very small. A weakly non-linear stability analysis is done to find Nusselt number governing the heat transport. Analytically the Ginzburg- landau amplitude equation is obtained for the stationary mode of convection. The effects of various parameters like Vadasz number, Mechanical and Thermal anisotropic parameters, Amplitude of oscillation, Frequency of modulation and Aspect ratio of cavity on heat transport is studied. It is observed that the heat transport can also be controlled by suitably adjusting the external and internal parameters of the system.

2. PROBLEM FORMULATIONS

We consider an anisotropic porous cavity of depth H and width L with stress free boundaries which is heated from below and cooled from above. The X-axis is taken along the lower boundary and the Z-axis is vertically upward. The lower surface is held at temperature To+ΔT while the upper surface is at To. A uniform positive adverse temperature gradient ΔT is maintained between the lower and upper surfaces. The Brinkman- Darcy model which includes the time derivative term is employed in the momentum equation. The continuity and momentum equations governing the motion of an incompressible fluid are given by

$$\nabla . q = 0 \tag{1}$$

$$\frac{1}{\varepsilon}\frac{\partial q}{\partial t} = -\frac{1}{\rho_o}\nabla p + \frac{\rho}{\rho_o} g - \frac{\nu}{K} q \tag{2}$$

$$\frac{\partial T}{\partial t}+(q.\nabla)T=\nabla.(k\nabla.T) \tag{3}$$

$$\rho=\rho_0[1-\alpha_T(T-T_0)] \tag{4}$$

where q is the velocity of fluid in porous medium, p is the fluid pressure, ε is the porosity, K is the permeability tensor $K_x(\hat{\imath}\hat{\imath}+\hat{\jmath}\hat{\jmath})+K_z(\hat{k}\hat{k})$, κ is the thermal diffusivity tensor $k_{Tx}(\hat{\imath}\hat{\imath}+\hat{\jmath}\hat{\jmath})+k_{Tz}(\hat{k}\hat{k})$, T is the temperature, ν is the kinematic viscosity, g is the modulated gravitational acceleration and is given by

$$g=g_0[1+\varepsilon^2\delta_1\cos(\Omega t)] \tag{5}$$

A Cartesian system (x, y, z) is used with Z- axis vertically upward in the gravitational field.

Assuming the basic state to be quiescent, the quantities at the basic state are given by
$q_b=(0,0,0),\quad p=p_b(z)$

$$T=T_b(z)\quad and\quad \rho=\rho_b(z) \tag{6}$$

satisfying the conditions $\frac{dp_b}{dz}=-\rho_b g,\quad \frac{d^2T_b}{dz^2}=0$ (7)

where b refers to the basic state.

The conduction state solutions are given by

$$T_b=1-z \tag{8}$$

Now superimpose the small perturbations at the basic state as

$$q=q_b+q',\qquad T=T_b+T',\qquad \rho=p_b+p',\qquad p=\rho_b+\rho' \tag{9}$$

where primes denote the quantities at the perturbed state. Putting Eq.9 in Eqs.1−4 and using solution of basic state Eq.6, the perturbed equations are obtained as

$$\nabla.q'=0 \tag{10}$$

$$\frac{1}{\varepsilon}\frac{\partial q'}{\partial t}=-\frac{1}{\rho_0}\nabla p'+g\alpha_T T'-\frac{\nu}{K}q' \tag{11}$$

$$\frac{\partial T'}{\partial t}+(q'.\nabla)T'+\frac{\partial T_b}{\partial z}=k_{Tx}\nabla^2T'+k_{Tz}\frac{\partial^2T'}{\partial z^2} \tag{12}$$

Now performing the non-dimensionalisation in Eqs.11 − 12 using the transformations

$$q'=\frac{kT_z}{H}q^*,\qquad p'=\frac{\mu kT_z}{K_z}p^*,\qquad T'=(\Delta T)T^*,\qquad (x,y,z)=H(x^*,y^*,z^*),\qquad t=\frac{H^2}{KT_z}t^*,\qquad \Omega=\frac{k_{Tz}}{H^2}\Omega^*$$

Eliminating pressure term by taking curl of Eq. (11) and introducing the stream function defined as $(u,v,w)=(\frac{\partial\Psi}{\partial z},0,-\frac{\partial\Psi}{\partial x})$, we get

$$\left[\frac{1}{Va}\frac{\partial}{\partial t}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)+\left(\frac{\partial^2}{\partial x^2}+\frac{1}{\xi}\frac{\partial^2}{\partial z^2}\right)\right]\Psi+Ra(1+\varepsilon^2\delta_1\cos\Omega t)\frac{\partial T}{\partial x}=0 \tag{13}$$

$$\left[\frac{\partial}{\partial t}-\left(\eta\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)\right]T=-\frac{\partial\Psi}{\partial x}+\frac{\partial(\Psi,T)}{\partial(x,z)} \tag{14}$$

where $Va=\varepsilon Pr/Da$ is Vadsaz number, $Ra=\frac{\alpha_T(\Delta T)gHK_Z}{\varepsilon\nu\kappa_{Tx}}$ is the Rayleigh number and $Da=Kz/L^2$ is the Darcy number.
Assuming boundaries are stress free and isothermal, therefore the boundary conditions are given by

$$\Psi=\frac{\partial^2\Psi}{\partial z^2}=0\ at\ z=0\ and\ z=1 \tag{15}$$

$$T=1\ at\ z=0\ and\ T=0\ at\ z=1 \tag{16}$$

$$\frac{\partial T}{\partial x}=0 \;\; at \;\; x=0 \;\; and \;\; x=Ar \tag{17}$$

Now rescaling time $\tau=\varepsilon^2 t$ to keep the time variation slow. Let $\Omega=\frac{\omega}{\varepsilon^2}$. The Eqs. (13) and (14) can be written as

$$\left(\frac{\varepsilon^2}{Va}\frac{\partial}{\partial\tau}\nabla^2+{\nabla_\xi}^2\right)\Psi+Ra(1+\varepsilon^2\delta_1\cos\omega\tau)\frac{\partial T}{\partial x}=0 \tag{18}$$

$$\left[\varepsilon^2\frac{\partial}{\partial\tau}-{\nabla_\eta}^2\right]T=-\frac{\partial\Psi}{\partial x}+\frac{\partial(\Psi,T)}{\partial(x,z)} \tag{19}$$

where $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}$, $\quad {\nabla_\xi}^2=\frac{\partial^2}{\partial x^2}+\frac{1}{\xi}\frac{\partial^2}{\partial z^2}$, $\quad {\nabla_\eta}^2=\eta\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}$;

3. AMPLITUDE EQUATION (GINZBURG- LANDAU EQUATION) AND HEAT TRANSPORT

Introduce following asymptotic equations in the Eqs. (18) and (19)

$$\left.\begin{aligned} Ra&=Ra_0+\varepsilon^2 Ra_2+\cdots\\ \Psi&=\varepsilon\Psi_1+\varepsilon^2\Psi_2+\cdots\\ T&=\varepsilon T_1+\varepsilon^2 T_2+\cdots\end{aligned}\right\} \tag{20}$$

where Ra_0 is the critical Rayleigh number at which convection sets in without modulation. Putting Eq. (20) in Eqs. (18) and (19). At lowest order ε equations are

$$\begin{bmatrix}\nabla_\xi^2 & Ra_0\frac{\partial}{\partial x}\\ \frac{\partial}{\partial x} & -\nabla_\eta^2\end{bmatrix}\begin{bmatrix}\Psi_1\\ T_1\end{bmatrix}=\begin{bmatrix}0\\0\end{bmatrix} \tag{21}$$

This is corresponding to linear stability equations for stationary anisotropic porous convection and solution of the above equations can be written as

$$\left.\begin{aligned}\Psi_1(x,z,\tau)&=A(\tau)\sin\left(\frac{\pi x}{Ar}\right)sin(\pi z)\\ T_1(x,z,\tau)&=-\frac{Ar}{\pi(\eta+Ar^2)}A(\tau)\;\cos\left(\frac{\pi x}{Ar}\right)\sin(\pi z)\end{aligned}\right\} \tag{22}$$

where critical Rayleigh number for anisotropic porous convection in the absence of gravity modulation is given by

$$Ra_0=\frac{\pi^2(\xi+Ar^2)(\eta+Ar^2)}{\xi Ar^2} \tag{23}$$

At the second order we have,

$$\begin{pmatrix}\nabla_\xi^2 & Ra_0\frac{\partial}{\partial x}\\ \frac{\partial}{\partial x} & -\nabla_\eta^2\end{pmatrix}\begin{bmatrix}\Psi_2\\ T_2\end{bmatrix}=\begin{bmatrix}R_{21}\\ R_{22}\end{bmatrix} \tag{24}$$

$$R_{21}=\frac{1}{Va}\frac{(\partial\Psi_1,\nabla^2\Psi_1)}{\partial(x,z)}=0 \tag{25}$$

$$R_{22}=\frac{\partial(\Psi_1,T_1)}{\partial(x,z)}=\frac{-\pi}{2(\eta+Ar^2)}[A(\tau)]^2\;\sin(2\pi z) \tag{26}$$

We can obtain second order solution as

$$\left.\begin{aligned}\Psi_2&=0\\ T_2&=-\frac{[A(\tau)]^2}{8\pi(\eta+Ar^2)}\sin(2\pi z)\end{aligned}\right\} \tag{27}$$

The horizontally-averaged Nusselt number $Nu(\tau)$ for the anisotropic porous convection is given by

$$Nu(\tau)=\frac{\left[2Ar\int_{x=0}^{Ar}(1-z+T_2)_z dx\right]_{z=0}}{\left[2Ar\int_{x=0}^{Ar}(1-z)_z dx\right]_{z=0}} \tag{28}$$

Now substituting Eq. (27) in Eq. (28) and solving the integration, we get $\mathrm{Nu}(\tau) = 1 + \frac{[\mathrm{A}(\tau)]^2}{4(\eta+\mathrm{Ar}^2)}$

At the third order solution, we have

$$\begin{bmatrix} \nabla_\xi^2 & Ra_0 \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial x} & -\nabla_\eta^2 \end{bmatrix} \begin{bmatrix} \Psi_3 \\ T_3 \end{bmatrix} = \begin{bmatrix} R_{31} \\ R_{32} \end{bmatrix} \tag{30}$$

$$R_{31} = -(Ra_2 + Ra_0\delta_1 \cos(\omega\tau)) \frac{\partial T_1}{\partial x} - \frac{1}{Va}\frac{\partial(\nabla^2 \Psi_1)}{\partial \tau} \tag{31}$$

$$R_{32} = \frac{\partial \Psi_1}{\partial x}\frac{\partial T_2}{\partial z} - \frac{\partial T_1}{\partial \tau} \tag{32}$$

Substituting Ψ_1, T_1, T_2 from Eqs. (22) and (27) in Eqs.(31)-(32), we get

$$R_{31} = \left[\frac{-(Ra_2 + Ra_0\,\delta_1 \cos(\omega\tau))}{\eta + Ar^2} A(\tau) + \frac{\pi^2(Ar^2+1)}{Va\,Ar^2}\frac{dA}{d\tau}\right] \sin\left(\frac{\pi x}{Ar}\right) \sin(\pi z) \tag{33}$$

$$R_{32} = \left[\frac{Ar}{\pi(\eta + Ar^2)}\frac{dA}{d\tau} - \frac{\pi}{4Ar(\eta + Ar^2)} A^3(\tau)\cos(2\pi z)\right] \cos\left(\frac{\pi x}{Ar}\right) \sin(\pi z) \tag{34}$$

Adjoin of Eq. (21) is obtained. The solutions of adjoin so obtained are as

$$\left.\begin{aligned} \hat{\Psi}_1(x,z,\tau) &= -A(\tau)\sin\left(\tfrac{\pi x}{Ar}\right)\sin(\pi z) \\ \hat{T}_1(x,z,\tau) &= -\tfrac{Ar}{\pi(\eta+Ar^2)} A(\tau)\,\cos\left(\tfrac{\pi x}{Ar}\right)\sin(\pi z) \end{aligned}\right\} \tag{35}$$

where $\hat{\Psi}_1$, $\hat{T}_1$ denotes solutions of adjoins.

The solvability condition for the third order solution is given as

$$\int_{z=0}^{1}\int_{x=0}^{Ar}[\hat{\Psi}_1 \;\; R_{31} + Ra_0\,\hat{T}_1 R_{32}]dxdz = 0 \tag{36}$$

Now substituting Eqs. (33)- (35) into the Eq.(36), we get the autonomous Ginzburg- Landau equation for stationary instability with a time periodic coefficient in the form

$$\left[\frac{\pi^2(Ar^2+1)}{VaAr^2} + Ra_0\frac{Ar^2}{\pi^2(\eta + Ar^2)^2}\right]\frac{dA(\tau)}{d\tau} - f(\tau)A(\tau) + \frac{Ra_0}{8(\eta + Ar^2)^2}A^3(\tau) = 0 \tag{37}$$

where

$$f(\tau) = \frac{Ra_2 + Ra_0\delta_1\cos(\omega\tau)}{\eta + Ar^2} \tag{38}$$

The solution of Eq.(37) is obtained using fourth order Runge-Kutta method numerically subject to the initial condition $A(0) = a_0$, where a_0 is a chosen initial amplitude of convection. We have assumed that $Ra_2 = Ra_0$ to keep the parameters to be minimum.

4. RESULT AND DISCUSSIONS

In this paper, we have studied the effect of gravity modulation on thermal instability in anisotropic porous cavity. A weakly non linear instability analysis is done to study the heat transfer under different regimes. The effect of different parameters Vadasz number (Va), thermal anisotropic parameter (η), mechanical anisotropic parameter (ξ), amplitude of gravity modulation (δ_1), frequency of modulation (ω) and Aspect ratio (Ar) on heat transfer with respect to rescaled time is done. The effect of gravity modulation on heat transport is shown in figures (1) to (6) by varying one by one each parameter. The values of different intrinsic and extrinsic parameters of the system are taken Va = 1, $\eta = 0.5$, $\xi=0.5$, $\delta1=0.1$, $\omega=2$, Ar=1 from Bhadauria *et.al*. [2] so that it has physical significance. The graph of Nusselt number (Nu) with respect to rescaled time (τ) is drawn. The figures show that the gravity modulation destabilizes the onset of convection i.e. heat transport is more in case of absence of gravity modulation. The results obtained are in line with Yang [29], Malashetty *et. al.* [20], [21] and Bhadauria *et.al.* [2].

1. Effect of Vadasz number (Va) is to destabilize the system as it increase with increase in heat transfer. From fig.1, we observe that as the Vadasz number increases from 0.5 to 1.5, the rate of heat transport increase. So, Vadasz number and heat transfer are proportional for the smaller values of time. After some time the heat transfer becomes constant independent of Vadasz number (Va).The result coincides with Vadasz [27] and Bhadauria *et.al.* [2].
2. Increase in the Thermal anisotropic parameter (η) suppresses the heat transport. Fluid flow through porous cavity decreases in vertical direction in comparison to the horizontal direction. This delays the convection and thus decreases the heat transport. From fig.2, we observe that as the anisotropic parameter (η) increases from 0.5 to 1.5, the rate of heat transfer decreases as the time passes.
3. Increase in Mechanical anisotropic parameter (ξ) is in line with heat transfer which is compatible with result of Ephere [12] and Bhadauria *et. al.* [2]. From fig.3, we observe that when mechanical anisotropic parameter (ξ) increases from 0.5 to 1.5, at small time the effect of mechanical anisotropic parameter (ξ) is similar to that of thermal anisotropic parameter (η). When time passes the heat transfer becomes constant independent of mechanical anisotropic parameter. We find that an increment in mechanical anisotropic parameter decreases heat transfer that suppress the convection and thus decreases the heat transfer.
4. From fig.4, we observe that when amplitude of gravity modulation (δ_1) increases from 0.1 to 0.3, the heat transfer increases. It is observed that effect of increase in amplitude of gravity modulation is to increase the heat transfer and thus advances the convection.
5. From fig.5, it is observed that increase in the frequency of modulation (ω) decreases the magnitude of Nusselt number and shortens the wavelength of oscillation. As the frequency of modulation (ω) increases from 1.5 to 15, the magnitude of Nusselt number decreases and the effect of modulation in heat transfer diminishes. On further increasing the value of frequency of modulation, the effect of gravity modulation in thermal instability suppresses convection. The result is in line with Yang [29].
6. From fig.6, it is found that as the Aspect ratio (Ar) of the anisotropic porous cavity increases from 0.5 to 15, the heat transfer decreases in first phase. But after sometime the effect on heat transfer diminishes with increase in Aspect ratio and becomes steady.

5. CONCLUSIONS

In this paper, we have investigated the effect of gravity modulation as Bernard- Darcy convection in anisotropic porous cavity and performed a weak non linear stability analysis using Ginzburg- landau amplitude equation. The conclusion is that by properly adjusting the different parameters in model we can control the heat transfer. They are as follows:

(1) Effect of gravity modulation is oscillatory in nature on heat transport.
(2) Effect of Vadasz number (Va) is to increase the heat transport in beginning of convection but reaches to steady state afterwards.
(3) Heat transport decreases with increase in mechanical anisotropic parameter (ξ) which is similar to that of thermal anisotropic parameter (η) in the beginning of convection but differs afterwards.
(4) Effect of an increment in the amplitude of modulation (δ_1) is to increase the heat transport.
(5) Increase in frequency of modulation (ω) decreases the heat transport.
(6) Heat transport increases with increase in Aspect ratio (Ar) in starting of convection but becomes steady after some time.

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Graph of Nusselt number (Nu) with respect to rescaled time (τ) for different intrinsic and extrinsic parameters of the system as $\text{Va} = 1,\ \eta = 0.5,\ \xi = 0.5,\ \delta_1 = 0.1,\ \omega = 2,\ \text{Ar} = 1$.

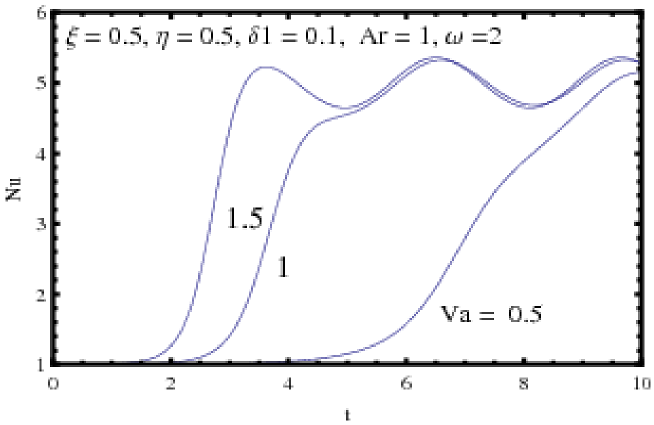

Figure 1: Effect of Vadasz number

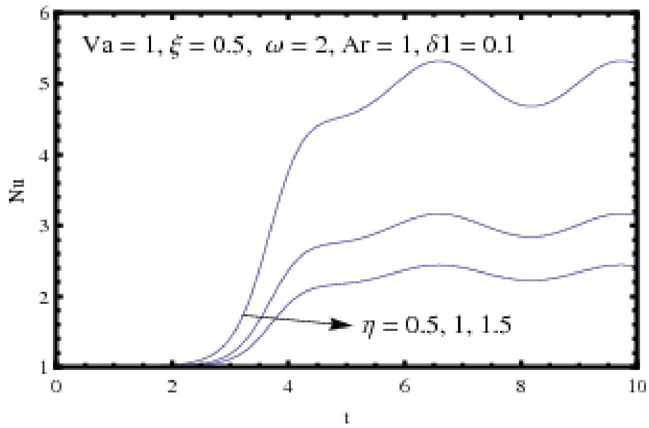

Figure 2: Effect of Thermal anisotropic parameter

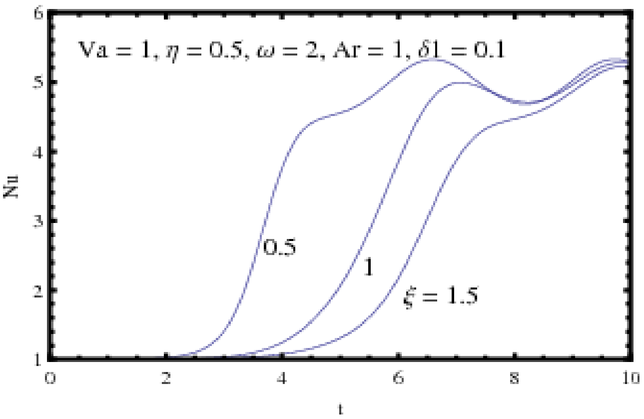

Figure: 3: Effect of Mechanical anisotropic parameter

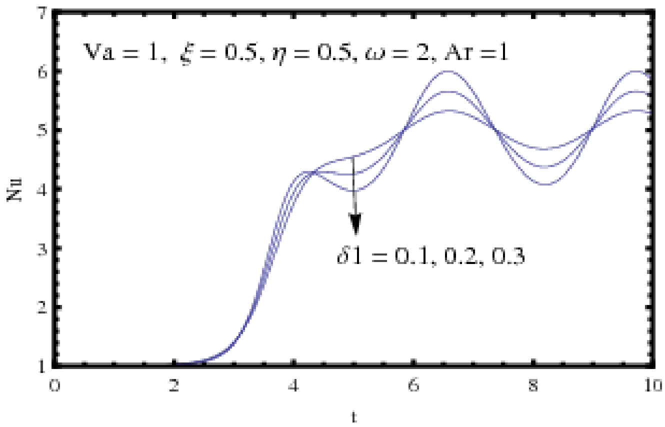

Figure: 4: Effect of Amplitude of modulation

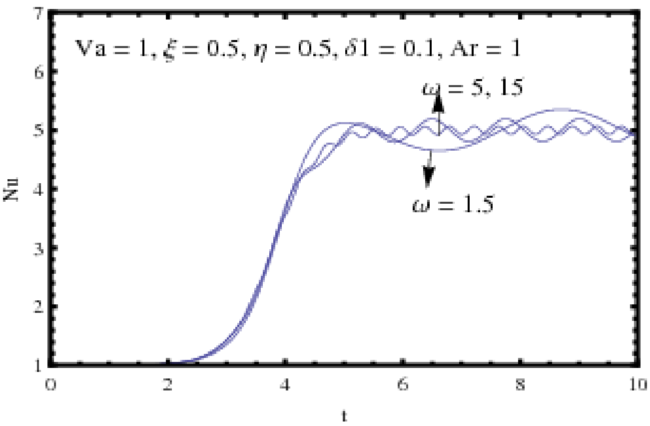

Figure: 5: Effect of Frequency of modulation

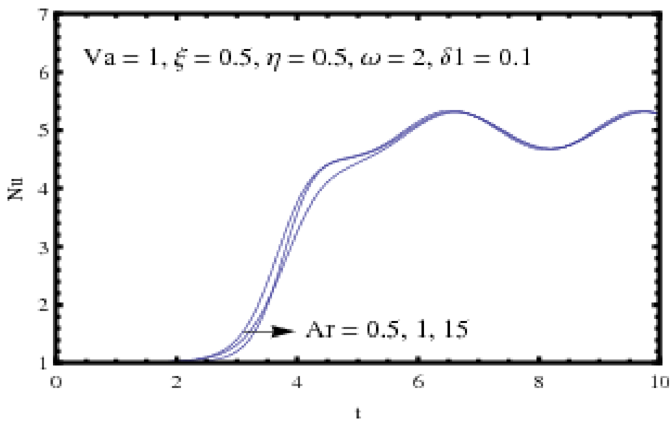

Figure: 6: Effect of Aspect ratio

Source of support: Nil, Conflict of interest: None Declared