ISSN 2394-3777 (Print)
ISSN 2394-3785 (Online)
Available online at www.ijartet.com

International Journal of Advanced Research Trends in Engineering and Technology (IJARTET)
Vol. 5, Special Issue 12, April 2018

Weak nonlinear thermal instability in a Dielectric fluid layer under temperature modulation

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Abstract: This The effect of temperature modulation on Rayleigh Benard convection with dielectric fluid is investigated. A local nonlinear theory presented using Ginzburg-Landau model. Instability and heat transfer in the medium depends not only on system parameters but also on modulation parameters. It is found that, a small variation in modulation parameters (δ_1, φ, ω) there is a significant effect on heat transfer in the system. The nature of Dielectric fluid is to stabilize the system. It is found that IPM (synchronous boundaries) is negligible on heat transport while OPM, LBMO (asynchronous boundaries) is to regulate heat transport.

Keywords: Thermal modulation, Dielectric liquid, Nusselt number, Amplitude equation.

I. Introduction

Magneto-convection in a fluid layer has been extensively investigated by Chandrasekhar (1961). Numerous practical engineering problems in which the temperature gradient is a function of both space and time. This non-uniform temperature gradient can be achieved by solving the energy equation with suitable time dependent thermal boundary conditions and can be used as an effective external mechanism to control the convective flow. However, in practice, the non-uniform temperature gradient finds its origin in transient heating or cooling at the boundaries. Hence the steady state temperature depends explicitly on position and time. This problem, called the temperature modulation problem, involves the solution of the energy equation under suitable time dependent boundary conditions. Predictions exist for a variety of responses to modulation depending on the relative strength and rate of forcing. Among these, there is the upward or downward shift of convective threshold compared to the un-modulated problems. Lot of work is available in the literature covering how a time periodic boundary temperature affects the onset of Rayleigh Benard convection. An excellent review related to this problem is given by Davis (1976).

Venezian (1969) was the first person who investigated thermal instability in a fluid layer under temperature modulation considering linear theory, he was motivated by the experiment of Donnelly (1964), in which, he investigated the effect of rotation speed modulation on the onset of instability in fluid flow between two concentric cylinders. However, the rotation speed modulation was the originating idea of the temperature modulation. Gershuni and Zhukhovitskii (1963) investigated the stability of equilibrium of a plane horizontal layer of fluid with a periodically varying temperature gradient obeying rectangular law. Rosenblat and Herbert (1970), investigated the linear stability problem and found an asymptotic solution by considering low frequency modulation and free free boundaries. Rosenblat and Tanaka (1971), studied the linear stability for a fluid in a classical geometry of Benard by considering the temperature modulation of rigid-rigid boundaries. The first nonlinear stability problem in a horizontal fluid layer, under temperature modulation was studied by Roppo et al. (1984). Bhadauria and Bhatia (2002), studied the effect of

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ISSN 2394-3785 (Online)
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temperature modulation on thermal instability by considering rigid rigid boundaries and different types of temperature profiles. Malashetty and Swamy (2008), investigated thermal instability of a heated fluid layer subject to both boundary temperature modulation and rotation. Bhadauria et al. (2009), studied the non-linear aspects of thermal instability under temperature modulation, considering various temperature profiles. Raju and Bhattacharyya (2010), investigated onset of thermal instability in a horizontal layer of fluid with modulated boundary temperatures by considering rigid boundaries. Bhadauria et al.(2012) studied temperature or gravity modulated non-linear stability problem in a rotating viscous fluid layer, using Ginzburg-Landau equation for stationary convection. Bhadauria et al.(2013) analyzed the effect of temperature dependant viscosity on thermal instability under temperature modulation by employing Darcy model. Bhadauria and Kiran (2014) investigated nonlinear double diffusive thermal instability in an electrically conducting fluid layer under thermal modulation.

Dielectric liquids are widely used as electrical insulators in high voltage applications, such as transformers, capacitors, high voltage cables, and switchgear (namely high voltage switchgear). The application of a strong electric field in a poorly conducting fluid can induce bulk amount of motions. This phenomenon known as electro convection or electro hydrodynamics, according to Paschkewitz (1998) the above phenomenon is gaining importance due to the technological stimulus of designing more efficient heat exchangers as required for jet engines. This phenomenon as boiling of dielectric liquids is an effective and promising cooling mechanism for future microelectronic chips Hetsroni (1990) and Hollen (1995). The dielectric fluid motor is attractive as a source of mechanical energy in a micro-machine, where the efficiency of energy transformation from electric to kinetic energy is very high Otsubo et al.(1997). Since magnetic fields and switching circuits are not required the dielectric fluid motor enhances size reduction and hence is an attractive source of mechanical energy in a micro machine. Convective heat transfer through polarized dielectric liquids were studied by Stiles et al.(1991,1997). They found that temperature drop between an electrically insulating layer of a dielectric liquid increases the fraction of the heat transfer associated with convection is found to pass through a maximum value when the critical horizontal wave number is close to 4 times its value when gravity is absent. For magneto-convection concerns Siddheshwar and Pranesh (2002), analyzed the role of magnetic field in the inhibition of natural convection driven by combined buoyancy and surface tension forces in a horizontal layer of an electrically conducting Boussinesq fluid with suspended particles confined between an upper free/adiabatic and a lower rigid/isothermal boundary is considered in 1g and μ_g situations. Bhadauria (2006), studied the effect of temperature modulation under vertical magnetic field by considering rigid boundaries. Bhadauria et al. (2010), investigated magneto-double diffusive convection in an electrically conducting fluid saturated porous medium with temperature modulation of the boundaries. Bhadauria and Sherani (2008, 2010), investigated onset of Darcy-convection in a magnetic fluid-saturated porous medium subject to temperature modulation of the boundaries and magneto-convection in a porous medium under temperature modulation.

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A series of work on dielectric fluid layer under modulation is given by Siddheshwar et al.(2007), where they investigated thermal instability of dielectric fluid when the layer is subjected to gravity modulation. The effect of both temperature and gravity modulation on heat transport in the problem of magneto convection in a Newtonian fluid was analyzed by Siddheshwar et al. (2012, 2013). One may notice that Siddheshwar et al.(2009) is considered time periodic thermal boundary conditions in a dielectric fluid layer and presented onset convection. But, heat transfer results are missing. As a consequence it is required to study nonlinear theory in order to understand heat transfer in the system. With this concept we have investigated a weak nonlinear theory while employing non autonomous Ginzburg-Landau equation.

II. Governing Equations

We consider an infinite horizontal dielectric fluid layer of depth'*d*' that supports a temperature gradient and an ac electric field in the vertical direction. The upper and lower boundaries are maintained at sinusoidally varying temperatures profile given bellow. For mathematical understanding and tractability we confine ourselves to study two-dimensional rolls so that all physica l quantities are independent of *y*, a horizontal co-ordinate. Further, the boundaries are assumed to be free and perfect conductors of heat. In this paper we assume the effective viscosity μ to be constant and the reference viscosity μ_1 will be used to denote the constant viscosity. Under the Boussinesq approximation, the dimensional governing equations are [Siddheshwar et al.(2013)]:

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

$$\rho_0\left(\frac{\partial\vec{q}}{\partial t} + (\vec{q}.\nabla)\vec{q}\right) = -\nabla p + \rho\vec{g} + \left(\vec{P}.\nabla\right)\vec{E} + \mu_1\nabla^2\vec{q}, \tag{2}$$

$$\rho_0\, C_{V,E}\left(\frac{\partial T}{\partial t} + (\vec{q}.\nabla)T\right) = k_T\nabla^2 T, \tag{3}$$

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

$$\nabla.\vec{D} = 0, \nabla\times\vec{E} = 0, \tag{5}$$

and $\vec{P} = \varepsilon_0(\varepsilon_r - 1)\vec{E}$.

The equation of state for dielectric constant ϵ_r is:

$$\varepsilon_r = \varepsilon_r^0 - e(T - T_0), \tag{6}$$

Where $\vec{E}$ is an ac electric field, C(V E) is an effective heat capacity at constant volume and electric field, $\overrightarrow{E_0}$ is the root mean square value of the electric field at the lower surface, k_T is thermal conductivity,$\vec{P}$ is dielectric polarisation and β_T is thermal expansion coefficient. We note here that the assumed Strength $\vec{E}$ of is such that it does not induce any non-Newtonian characteristics in the dielectricliquid. It is expedient to write $\varepsilon_r^0 = (1 + \chi_e)$, where χ_e is the electric susceptibility, for it enablesus to arrive at the conventional definition $\vec{P} = \varepsilon_r^0\chi_e\vec{E}$ in the absence of the temperature dependence of ε_r , that is, when e = 0. We continue using Eq. (6) with ε_r^0 replaced by $(1 + \chi_e)$. In writing Eq.(6) we have assumed that ε_r varies with the electric field strength quite insignificantly (Stiles et al.,1993). The externally imposed thermal boundary conditions, considered in this paper are given by (Venezian (1969)):

$$T = T_0 + \frac{\Delta T}{2}[1 + \varepsilon^2\delta_1\cos(\omega t)] \quad \text{at } z=0$$
$$= T_0 - \frac{\Delta T}{2}[1 - \varepsilon^2\delta_1\cos(\omega t + \emptyset)] \quad \text{at } z=d \tag{7}$$

where δ_1 represents the amplitude of temperature modulation, ω is modulation frequency and $\emptyset$ is the phase difference. The electric boundary conditions are that the normal component of the electric displacement $\vec{D}$ and tangential component of the electric field $\vec{E}$ are continuous across the boundaries. Taking the components of polarization and electric field in the basic state to be $[0, P_b(z)]$and $[0,E_b(z)]$, we obtain the conduction state solutions as:

$$\overrightarrow{q_b} = (0,0), \tag{8}$$

$$T_b(z,t) = T_0 + \frac{\Delta T}{2}\left(1 - \frac{2z}{d}\right) + \varepsilon^2\delta_1 Re[f_1(z,t)], \tag{9}$$

$$\vec{E}_b = \frac{(1+\chi_e)E_0}{(1+\chi_e) + e(1-\frac{z}{d})\Delta T}\hat{k}, \tag{10}$$

$$\vec{P}_b = \varepsilon_0\vec{E}(1 + \chi_e)(1 - \frac{1}{(1+\chi_e)+(1-\frac{z}{d})\Delta T})\hat{k}, \tag{11}$$

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Vol. 5, Special Issue 12, April 2018

where E0 is the root mean square value of the electric field at the lower surface. Now, we impose finite amplitude perturbations to the basic state of the form:

$$\vec{q} = \vec{q}_b + \vec{q}', \rho = \rho_b + \rho', p = p_b + p', \vec{P} = \vec{P}_b + (P_1', P_3'), \vec{E} = \vec{E}_b + (E_1', E_3') \qquad (12)$$

where primes denote the quantities at the perturbations,

and now the quantities (P_1', P_3'),leads to

$$P_1' = \varepsilon_0 \chi_e E_1' - e\varepsilon_0 T' E_1',$$

$$P_3' = \varepsilon_0 \chi_e E_3' - e\varepsilon_0 T' E_0' - e\varepsilon_0 T' E_3', \qquad (13)$$

where it has been assumed that $e\Delta T \ll (1 + \chi_e)$. Further, we consider only two dimensional disturbances in our study and hence the stream function can be drawn from Eq. (1) and introducing the perturbed electric potential Φ' through the relation $\vec{E}' = \nabla \boldsymbol{\varphi}'$, eliminate density and pressure terms from Eq.(2) and the resulting system is non-dimensionalized using the following scaling: $(x'y'z') = d(x^* y^* z^*), \psi = \kappa_T \psi^*, t = \frac{d^2}{\kappa_T} t^*$, $\vec{q}' = \frac{\kappa_T}{d} \vec{q}^*, T' = \Delta T^*$, and $\boldsymbol{\varphi}' = \frac{\varepsilon E_0 \Delta T d}{(1+\chi_e)} \boldsymbol{\varphi}^*$. For simplicity, we drop the asterisk, then the non-dimensionalized governing equations derived from Eqs. (1) -(6) are:

$$-\nabla^4\Psi+(Ra_T+R_E)\frac{\partial T}{\partial x}-R_E\frac{\partial^2 \varphi}{\partial x \partial z}=-\frac{1}{Pr}\frac{\partial}{\partial t}\nabla^2\Psi+R_E\frac{\partial(T,\frac{\partial \varphi}{\partial z})}{\partial(x,z)}+\frac{1}{Pr}\frac{\partial(\Psi,\nabla 2\Psi)}{\partial(x,z)} \qquad (14)$$

$$\frac{-\partial Tb}{\partial z}\frac{\partial \Psi}{\partial x}-\nabla^2 T=-\frac{\partial T}{\partial t}+\frac{\partial(\Psi,T)}{\partial(x,z)} \qquad (15)$$

$$\frac{-\partial T}{\partial z}-\nabla^2 \boldsymbol{\varphi} = 0 \qquad (16)$$

where the non-dimensionalized numbers are $Pr=\nu/k_T$ is Prandtl number, $Ra_T=\alpha_T g\Delta T d^3/\nu k_T$ is the thermal Rayleigh number and $R_E=\varepsilon(eE_0\Delta Td)^2/\mu_1 k_T(1+\chi_E)$ is the electric Rayleigh number. The Eq.(15) shows the basic state solution temperature influences the stability problem. Since, we assume small variations of time, therefore re-scaling it as $t=\varepsilon^2\tau$. The considered stress free and isothermal boundary conditions to solve the Eqs.(14)-(16) are:

$$\Psi=\partial^2\Psi/\partial z^2=T=0 \text{ at } z=0, z=1. \qquad (17)$$

III. Finite Amplitude Equation and Heat Transport

We introduce the following asymptotic expansions in Eqs.(14)-(16).

$$Ra_T=R_0+\varepsilon R_1+\varepsilon^2 R_2+\varepsilon^3 R_3+\ldots\ldots,$$
$$\Psi=\varepsilon\Psi_1+\varepsilon^2\Psi_2+\varepsilon^3\Psi_3+\ldots\ldots,$$
$$T=\varepsilon T_1+\varepsilon^2 T_2+\varepsilon^3 T_3+\ldots\ldots,$$
$$\boldsymbol{\varphi}=\varepsilon\,\boldsymbol{\varphi}_1+\varepsilon^2\,\boldsymbol{\varphi}_2+\varepsilon^3\,\boldsymbol{\varphi}_3+\ldots\ldots, \qquad (18)$$

where R_0 is the critical value of the Rayleigh number at which the onset of convection takes place in the absence of temperature modulation. Now, we solve the system for different orders of ε. At the lowest order, we consider the following solution (the readers may refer Bhadauria and Kiran (2013, 2014):

$$\Psi_1=-c/a\,\mathbf{A}\sin(ax)\sin(\pi z)., \qquad (19)$$
$$T_1=A\cos(ax)\sin(\pi z)., \qquad (20)$$
$$\Phi_1=\pi/c\,\mathbf{A}\cos(ax)\cos(\pi z)., \qquad (21)$$

where $c=a^2+\pi^2$.

The critical value of the Rayleigh number for the onset of convection in the absence of temperature modulation is: $R_0=c^3/a^2-R_E a^2/c$. If $R_E=0$, we obtained the classical results of Rayleigh-Benard convection obtained by Chandrasekhar (1961). Here *a* critical value of the wave number and is defied while minimizing R_0 with respect to *a*. For second order system, following the similar analysis of Bhadauria et al.(2013) and Siddheshwar et al.(2013), subjected to the boundary conditions given in Eq.(17), we obtain the following results

$$\Psi_2=0.,$$
$$T_2=-c/8\pi\,\mathbf{A}^2(\boldsymbol{\tau})\,\mathbf{sin}(2\pi z)., \qquad (22)$$
$$\Phi_2=0., \qquad (23)$$

The horizontally averaged Nusselt number, Nu, for the stationary mode of convection is given by:

$$Nu=1+(c/a)\,\mathbf{A}^2(\boldsymbol{\tau}). \qquad (24)$$

Here, we notice that thermal modulation is effective at second order and affects the above Nusselt number. At the third order, we have solution of the following form (the readers may refer Bhadauria and Kiran (2013, 2014):

$$R_{31}=-\frac{1}{Pr}\frac{\partial}{\partial \tau}\nabla^2\Psi-R_2\frac{\partial T}{\partial x}+R_E\frac{\partial T2}{\partial z}\frac{\partial 2\,\varphi 1}{\partial x\partial z} \qquad (25)$$

$$R_{32}=-\frac{\partial T1}{\partial \tau}+\frac{\partial \Psi 1}{\partial x}\frac{\partial T2}{\partial z}+\boldsymbol{\delta}_1\,\mathbf{f}_1\frac{\partial \Psi 1}{\partial x} \qquad (26)$$

$$R_{33}=0, \qquad (27)$$

Substituting Ψ_1, T_1 and T_2 into Eqs.(25-27), we can obtain expressions for R_{31}, R_{32} and R_{33} easily. Now by

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ISSN 2394-3785 (Online)
Available online at www.ijartet.com

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applying the solvability condition for the existence of third order solution, we get the non autonomous Ginzburg-Landau equation for stationary convection with time-periodic coefficients in the form:

$$Q_1\frac{\partial A}{\partial \tau}= Q_2 A - Q_3 A \qquad (28)$$

where $Q_1=(1+Pr)/Pr$, $Q_2= a^2/c^2\, R_2-2c\, \boldsymbol{\delta_1}\, I(\tau)$, $Q_3= c^2/8+ R_E\, a^2\, \pi^2/8c^2$ and $I(\tau)=\int_0^1 f1 \sin^2(\pi z)\, dz$.

The Ginzburg-Landau equations given in Eq.(28) is Bernoulli equation and obtaining its analytical solution is not an easy task, due to its non-autonomous nature. So it has been solved numerically using the in-built function NDSolve of Mathematica, subjected to the initial condition A(0)=a0 where a0 is the chosen initial amplitude of convection. In our calculations we may use R2=R0, to keep the parameters to the minimum. We have calculated the mean value of Nusselt number (MNu) foe better understanding the effect of thermal modulation on heat transport, a representative time interval that allows a clear comprehension of the modulation effect needs to be chosen. The interval $(0,2\pi)$ seemed an appropriate interval to calculate MNu. The time-averaged Nusselt number MNu is defined as

$$MNu=1/2\pi\int_0^{2\pi} Nu\, d\tau. \qquad (29)$$

An interesting observation that can be observed in I1, that determines whether the modulation amplifies or diminishes the amplitude of convection. A discussion of the results now follows culminating in a listing of conclusions.

IV. Results and Discussion

This paper is an attempt to find temperature modulation effect on Rayleigh-Benard convection with dielectric fluid. A non-linear realm of convection has been considered to investigate heat transport in terms of Nusselt and mean Nusselt numbers as a function of system parameters. We consider a small amplitude temperature modulation is to discount possible oscillatory convection that might be triggered by large amplitude temperature modulation. We also assume low values of frequency of modulation where for low values of frequency heat transfer is maximum. The effect of the applied electric field comes through the electrical Rayleigh number R_E. Fredholm alternative condition is invoked for deriving Ginzburg-Landau equation in order to find an amplitude of convection, which is used to calculate Nu and MNu. The results have been presented here in two ways one for Nu and another for MNu. In Fig.1-4 the results are given for Nu as a function of time and by showing the individual parameter effect on Nu.

Figure 1 present heat transfer results corresponding (R_E, $\boldsymbol{\delta_1}$, $\boldsymbol{\omega}$). In Fig.1a the effect of R_E and in Fig.1b the effect of $\boldsymbol{\omega}$ is presented. It is found that, as the value of (R_E, $\boldsymbol{\omega}$) increases heat transfer decrease in the system. Indicating that the nature of dielectric fluid opposes the fluid motion in the system and the convection delays, as a consequence heat transfer decreases. In the case of frequency of modulation as $\boldsymbol{\omega}$ increased, the wave length becomes shortens and reduces heat transfer in the system.

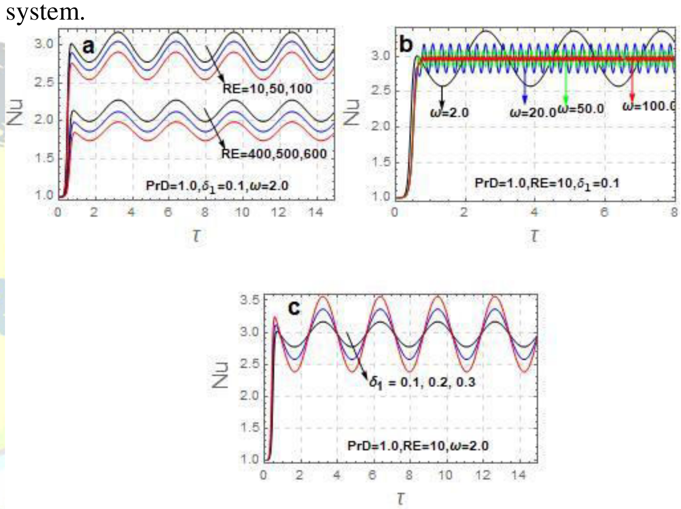

Fig .1 : Heat transfer results with respect to (RE, ω, δ_1)

The results are similar to Siddheshwar et al.(2007) for gravity modulation with the same model. The effect of amplitude $\boldsymbol{\delta_1}$ of modulation is presented in Fig.1c. It is found that, as $\boldsymbol{\delta_1}$ varies heat transfer increases in the system. The reader may understand that the concept of modulation may use to regulate heat transfer in the system. The same concept may be used to delay or advance onset of convection using linear theory reported by Siddheshwar et al.(2009).

A close observation on $\varnothing$ and $\boldsymbol{\omega}$ is made in order to understand the effect of modulation on mean Nusselt number. It is found that in Fig.2 and 3 for a given frequency of modulation there is a range of $\varnothing$ in which MNu increases with increasing $\varnothing$ and another range in which MNu decreases. Thus, one may conclude that, the combination of choices of $\boldsymbol{\omega}$ and $\varnothing$ can be made depending on the demands on heat transport in an application situation. Heat transfer can be regulated (enhanced or reduced) with the external mechanism of temperature modulation. Our results are compatible with

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results of Malashetty et al.(2002). We also can observe our results in Figs.5-7 are the results which are similar to Siddheshwar et al. (2013) for the ordinary fluid layer where R_E=0. The effect **Pr** is to destabilize the system and hence heat transfer.

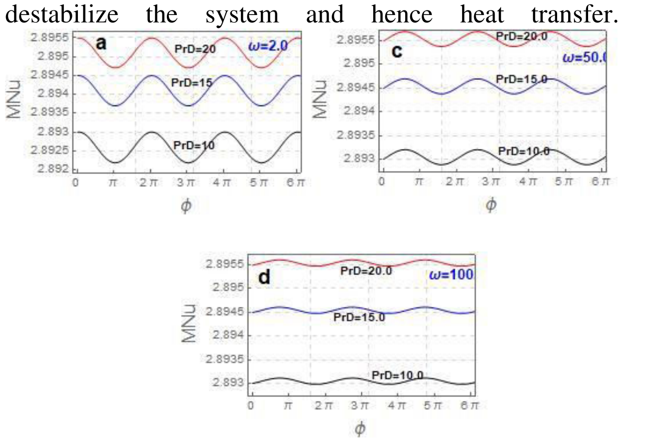

Fig .2 : Effect of ϕ on mean Nusseltnumber MNu for different values of ω and PrD

The values of **Pr** ranging from 1 to 20 to retain the inertial effects in the momentum equation. It is being observed from the figures, no modulation effect on Nu as there is an effect for lower values of time and becomes steady. Since there is no effect is being observed for IPM case of **δ_1, ω** we have omitted figure representation. The Nusselt number starts with 1 showing steady state and becomes unsteady showing convective regime in the medium.

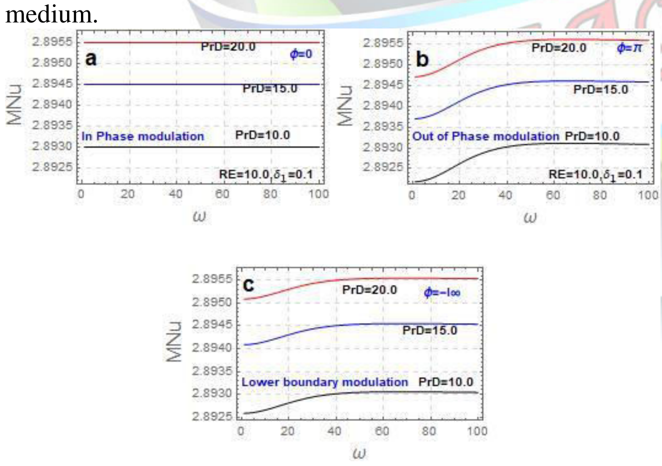

Fig .3 : Effect of modulation on $\overline{Nu}$ fordifferent values of ϕ and PrD

It is clear that for the case of thermal modulation (in Fig.4a), the boundary temperatures should not be in in-phase modulation (synchronized), where the effect of modulation is negligible on heat transport. The lower boundary case the results followed by OPM, but magnitude in Nu will be different in all the three cases given in Fig.4a. In Fig.4b it is observed that, Nu is obtained in terms of **ω** and the results conform the nature of ω as it is increases reduces the heat transfer in the system. To check the accuracy of our results, the present study results have been compared while solving an amplitude equation Eq.(28) with RKF45 and found best approximation presented in Fig.4c. The reader may also look at the studies of Venezian (1969), Bhadauria and Kiran (2013, 2014) for the results corresponding to temperature modulation.

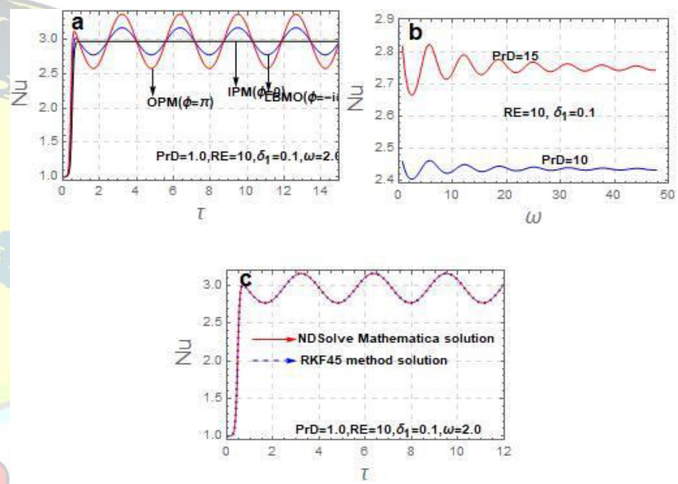

Fig .4 : Comparision of different profiles

V. CONCLUSIONS

A Weak nonlinear theory being investigated to study heat transport in dielectric fluid layer under thermal modulation. Ginzburg-Landau model was used to derive amplitude equation as a function of slow time and mean Nusselt number in terms of (**ω** and Ø). The following conclusions escribe our previous analysis:

1. In-phase modulation has no significance on heat transport hence it is negligible.
2. Asynchronous boundaries can be used effectively to regulate the system.
3. [MNu/Nu] (**δ_1**=0) ≈MNu/Nu(**δ_1**≠0) for IPM case.
4. MNu, Nu increases as Pr_D, **δ_1**, and decreases as **ω,** R_E increases.
5. For a better choice of the values of **ω** and Ø, heat transfer results may hold.

BIOGRAPHY

The author Dr. Palle Kiran is grateful to the Department of Atomic Energy, Government of India, New Delhi, for providing financial assistance in the form of NBHM-Post doctoral fellowship (Lett. No.: 2/40(27)/2015/R&D-II/401).

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