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Rayleigh-Bénard-Taylor Convection of Newtonian Nanoliquid

P. G. Siddheshwar, T. N. Sakshath

***Abstract*—In the paper we make linear and non-linear stability analyses of Rayleigh-Bénard convection of a Newtonian nanoliquid in a rotating medium (called as Rayleigh-Bénard-Taylor convection). Rigid-rigid isothermal boundaries are considered for investigation. Khanafer-Vafai-Lightstone single phase model is used for studying instabilities in nanoliquids. Various thermophysical properties of nanoliquid are obtained using phenomenological laws and mixture theory. The eigen boundary value problem is solved for the Rayleigh number using an analytical method by considering trigonometric eigen functions. We observe that the critical nanoliquid Rayleigh number is less than that of the base liquid. Thus the onset of convection is advanced due to the addition of nanoparticles. So, increase in volume fraction leads to advanced onset and thereby increase in heat transport. The amplitudes of convective modes required for estimating the heat transport are determined analytically. The tri-modal standard Lorenz model is derived for the steady state assuming small scale convective motions. The effect of rotation on the onset of convection and on heat transport is investigated and depicted graphically. It is observed that the onset of convection is delayed due to rotation and hence leads to decrease in heat transport. Hence, rotation has a stabilizing effect on the system. This is due to the fact that the energy of the system is used to create the component V. We observe that the amount of heat transport is less in the case of rigid-rigid isothermal boundaries compared to free-free isothermal boundaries.

***Keywords*—Nanoliquid, rigid-rigid, rotation, single-phase.

NOMENCLATURE

Latin symbols

C_p	specific heat at constant pressure
$\vec{g}$	acceleration due to gravity $(0, 0, -g)$
h	distance between the plates
k	thermal conductivity
p	pressure
$\vec{q}$	velocity vector $(u, 0, w)$
T	dimensional temperature
T_0	temperature of the upper plate(reference temperature)
u	dimensional horizontal velocity component
w	dimensional vertical velocity component
U	non-dimensional horizontal velocity component
W	non-dimensional vertical velocity component
x	dimensional horizontal coordinate
z	dimensional vertical coordinate
X	non-dimensional horizontal coordinate
Z	non-dimensional vertical coordinate

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Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
χ	volume fraction
ΔT	temperature difference
μ	dynamic viscosity
∇^2	Laplacian operator $(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2})$
ψ	stream function
Ψ	non-dimensional stream function
ρ	density
Θ	non-dimensional temperature

Subscripts

b	basic state
l	base liquid
nl	nanoliquid
np	nanoparticle
c	critical

I. INTRODUCTION

THE effect of rotation is shown to have a significant impact on the flow in porous media. The effect of Coriolis force on the onset of convection and extent to which it delays the onset of convection was examined by Chandrasekhar [8]. Experimental study that includes the stability of Rayleigh-Bénard convection over a wide range of Taylor numbers was conducted by Rossby [17]. Liu and Ecke [13] presented the experimental studies of turbulent thermal convection in water confined in a cell with a square cross section with and without rotation Some of the recent developments in bifurcation theory and their relevance to the study of rotating convection was summarized by Knobloch [12]. Thermal instablities of a fluid contained in rotating system are investigated by Busse [6]. Agarwal et al. [1] studied the thermal instability in a rotating anisotropic porous layer saturated by a nanofluid while the thermal instability in a rotating horizontal porous layer considering the effect of Brownian motion and thermophoresis was discussed by Bhadauria and Agarwal [3]. Galdi and Straughan [10] applied the nonlinear energy stability theory to study the stabilizing effect of rotation. Vadasz [20] carried out an analytical investigation of the Coriolis effect on three dimensional gravity-driven convection in a rotating porous layer using linear and weakly non linear stability theories. Beaume et al. [2] computed the non-linear solutions of the equations describing two-dimensional convection in a rotating horizontal layer with constant angular velocity. The stability of a rotating doubly diffusive fluid was studied by Pearlstein [15]. The influence of various parameters on convection in the presence of rotation, for both high and low rotation rates was discussed by Vanishree and Siddheshwar [21]. The effect of modulation of the rotation speed on the Rayleigh-Bénard instability was investigated by Bhattacharjee [4]. Cox and Matthews [9] described new instabilities arising in three related convection problems namely rotating convection, magnetoconvection and rotating magnetoconvection. Riahi [16] discussed the nonlinear convection in a porous medium and rotation about vertical axis. The preferred cellular pattern depending upon the rotation rate was reported by Veronis [22]. Tagare et al. [19], Yadav et al. [23] studied the effect of Coriolis force on gravity-driven convection for idealised stress-free boundary conditions. The influence of centrifugal force on a rotating convection system was examined by Lopez and Marques [14].

A. Mathematical Formulation

The schematic of the flow configuration is as shown in Fig. 1. The coordinate system is taken at the lower boundary with the z-axis taken vertically upwards and the x-axis along the plates. The system is rotated about the z-axis with uniform angular velocity $\overrightarrow{\Omega}$.

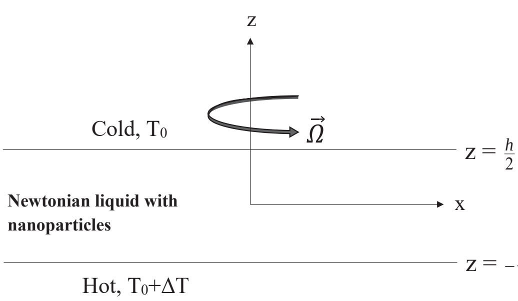

Fig. 1 Schematic representation of Rayleigh-Bénard-Taylor convection of Newtonian nanoliquid

The governing equations describing Rayleigh-Bénard-Taylor convection are:

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

$$\rho_{nl}(\overrightarrow{q}.\nabla)\overrightarrow{q} = -\nabla p + \mu_{nl}\nabla^2\overrightarrow{q} + \rho_{nl}\overrightarrow{g} + 2\rho_{nl}(\overrightarrow{q}\times\overrightarrow{\Omega}), \tag{2}$$

$$\alpha_{nl}\nabla^2 T = (\overrightarrow{q}.\nabla)T, \tag{3}$$

$$\rho_{nl}(T) = \rho_{nl}(T_0) - (\rho\beta)_{nl}(T - T_0), \tag{4}$$

where the nanoliquid properties are obtained from either phenomenological laws or mixture theory as given below:

a) Phenomenological laws

$$\frac{\mu_{nl}}{\mu_l} = \frac{1}{(1-\chi)^{2.5}}(\text{Brinkman model [5]}), \tag{5}$$

$$\frac{k_{nl}}{k_l} = \frac{\left(\frac{k_{np}}{k_l}+2\right) - 2\chi\left(1-\frac{k_{np}}{k_l}\right)}{\left(\frac{k_{np}}{k_l}+2\right) + \chi\left(1-\frac{k_{np}}{k_l}\right)} \tag{6}$$

(Hamilton-Crosser model [11]).

b) Mixture theory

$$\left.\begin{aligned} \alpha_{nl} &= \frac{k_{nl}}{(\rho C_p)_{nl}}, \\ \frac{\rho_{nl}}{\rho_l} &= (1-\chi) + \chi\,\frac{\rho_{np}}{\rho_l}, \\ \frac{(\rho C_p)_{nl}}{(\rho C_p)_l} &= (1-\chi) + \chi\frac{(\rho C_p)_{np}}{(\rho C_p)_l}, \\ \frac{(\rho\beta)_{nl}}{(\rho\beta)_l} &= (1-\chi) + \chi\frac{(\rho\beta)_{np}}{(\rho\beta)_l}, \end{aligned}\right\}. \tag{7}$$

1) Basic State Solution: We assume boundary conditions on $\overrightarrow{q}$ and T to be:

$$\overrightarrow{q} = 0,\ T = T_0 + \Delta T \text{ at z} = -\frac{h}{2},$$
$$\overrightarrow{q} = 0,\ T = T_0 \text{ at z} = \frac{h}{2}.$$

Taking the velocity, temperature, density and pressure in the quiescent basic state as follows:

$$\left.\begin{aligned} \overrightarrow{q} &= \overrightarrow{q}_b = (0,0) \\ p(z) &= p_b(z) \\ \rho(z) &= \rho_b(z) \\ T(z) &= T_b(z) \end{aligned}\right\}, \tag{8}$$

we obtain the quiescent state solution for the temperature in the form:

$$T_b(z) = T_0 + \Delta T\left(\frac{1}{2} - \frac{z}{h}\right). \tag{9}$$

We now superimpose perturbations on the quiescent basic state and so we write:

$$\left.\begin{aligned} \overrightarrow{q} &= \overrightarrow{q}_b + \overrightarrow{q}' \\ p &= p_b + p' \\ \rho &= \rho_b + \rho' \\ T &= T_b + T' \end{aligned}\right\}, \tag{10}$$

where the primes indicate a perturbed quantity. Now eliminating the pressure *p* between the *x*- and *y*-components of (2), introducing the stream function $\psi(x,z)$ in the form

$$u = \frac{\partial\psi}{\partial z} \text{ and } w = -\frac{\partial\psi}{\partial x}$$

and incorporating the quiescent state solution and non dimensionalizing the resulting equations as well as (3) using the following definition

$$(X,Z) = \left(\frac{x}{h},\frac{z}{h}\right),\ \Psi = \frac{\psi}{\alpha_l},\ \Theta = \frac{T}{\Delta T},\ V = \frac{vh}{\alpha_l},$$
$$U = \frac{uh}{\alpha_l}, W = \frac{wh}{\alpha_l},$$

we obtain the dimensionless form of governing equations as:

$$a_1\nabla^4\Psi - a_1^2 Ra_{nl}\frac{\partial\Theta}{\partial X} + a_1\sqrt{Ta}\frac{\partial V}{\partial Z} + \frac{1}{Pr_{nl}}\frac{\partial(\Psi,\nabla^2\Psi)}{\partial(X,Z)} = 0, \tag{11}$$

$$-\frac{\partial\Psi}{\partial X} + a_1\nabla^2\Theta + \frac{\partial(\Psi,\Theta)}{\partial(X,Z)} = 0, \tag{12}$$

$$\nabla^2 V - \sqrt{Ta}\frac{\partial \Psi}{\partial Z} + \frac{1}{Pr_{nl}}\frac{\partial(\Psi, V)}{\partial(X, Z)} = 0, \tag{13}$$

where V is the velocity in the y direction which vary along x and z directions,

$$\begin{aligned} a_1 &= \frac{\alpha}{\alpha_1}(\text{thermal diffusivity ratio}),\\ Ra_{nl} &= \frac{(\rho\beta)_{nl} h^3 g \Delta T}{\mu_{nl}\ \alpha_{nl}}(\text{nanoliquid Rayleigh number}),\\ Ta &= \left(\frac{2\rho_{nl}\Omega h^2}{\phi\mu_{nl}}\right)^2(\text{modified Taylor number}),\\ Pr_{nl} &= \frac{\mu_{nl}}{\rho_{nl}\alpha_{nl}}(\text{nanoliquid Prandtl number}). \end{aligned}$$

In the next section, we make a linear stability analysis and study the onset of convection.

B. Linear Stability Analysis

The boundary conditions suitable for rigid-rigid isothermal boundaries are:

$$\Psi = \frac{\partial \Psi}{\partial Z} = \Theta = V = 0\ at\ Z = \pm\frac{1}{2}. \tag{14}$$

The normal mode solution for solving eigen boundary value problem is:

$$\left.\begin{aligned} \Psi &= A\ sin(\nu X)\ (C_f)_e(Z),\\ \Theta &= B\ cos(\nu X)\ sin[\pi(Z+\frac{1}{2})],\\ V &= C\ sin(\nu X)\ z\ sin[\pi(Z+\frac{1}{2})], \end{aligned}\right\}, \tag{15}$$

where A, B and C are the amplitudes, ν is the wave number and $(C_f)_e(Z)$ is the Chandrasekhar function (even solution) [7] and μ_1=4.73004074 is the eigen value satisfying the following equation,

$$tanh\left(\frac{\mu_1}{2}\right) + tan\left(\frac{\mu_1}{2}\right) = 0. \tag{16}$$

Substituting (15) in the dimensionless form of the governing equations (11)-(13) and following the standard orthogonalization procedure, we obtain the expression of the critical value of nanoliquid Rayleigh number for stationary onset as:

$$\begin{aligned} Ra_{nlc} =& \frac{\delta_c^2\left(F_1\left(\nu_c^4+\mu_1^4\right)+2F_2\nu_c^2\mu_1^2\right)}{2F_3^2\nu_c^2}\\ &+ \frac{12\pi^4 F_4^2\ \delta_c^2\ Ta}{F_3^2\nu_c^2\left(-6\nu_c^2+\pi^2\left(\nu_c^2+6\right)+\pi^4\right)} \end{aligned} \tag{17}$$

where

$$\delta_c^2 = \nu_c^2 + \pi^2,$$

$$\begin{aligned} F_1 =& \frac{1}{1+\cos(\mu_1)} - \frac{\tan\left(\frac{\mu_1}{2}\right)}{\mu_1} + \frac{1}{1+\cosh(\mu_1)}\\ &- \frac{\tanh\left(\frac{\mu_1}{2}\right)}{\mu_1}, \end{aligned} \tag{18}$$

$$\begin{aligned} F_2 =& \frac{1}{1+\cos(\mu_1)} + \frac{\tan\left(\frac{\mu_1}{2}\right)}{\mu_1} - \frac{1}{1+\cosh(\mu_1)}\\ &- \frac{\tanh\left(\frac{\mu_1}{2}\right)}{\mu_1}, \end{aligned} \tag{19}$$

$$F_3 = \frac{4\pi\mu_1^2}{\pi^4 - \mu_1^4}, \tag{20}$$

$$\begin{aligned} F_4 =& \frac{8\left(\mu_1^4+\pi^4\right)\mu_1^2}{\left(\pi^4-\mu_1^4\right)^2} + \mu_1^3\left(\frac{\tan\left(\frac{\mu_1}{2}\right)}{\left(\pi^2-\mu_1^2\right)^2} - \frac{\tanh\left(\frac{\mu_1}{2}\right)}{\left(\mu_1^2+\pi^2\right)^2}\right)\\ &- \pi^2\mu_1\left(\frac{\tan\left(\frac{\mu_1}{2}\right)}{\left(\pi^2-\mu_1^2\right)^2} + \frac{\tanh\left(\frac{\mu_1}{2}\right)}{\left(\mu_1^2+\pi^2\right)^2}\right). \end{aligned} \tag{21}$$

The non-linear analysis will now be used to study the enhancement of heat transport.

C. Weakly Non-Linear Stability Analysis

The truncated representation for making a weakly non-linear analysis for rigid-rigid, isothermal boundaries is

$$\left.\begin{aligned} \Psi &= A\ sin(\nu_c X)\ (C_f)_e(Z),\\ \Theta &= B\ cos(\nu_c X)\ sin[\pi(Z+\frac{1}{2})] + C\ sin[2\pi(Z+\frac{1}{2})],\\ V &= D\ sin(\nu_c X)\ z\ sin[\pi(Z+\frac{1}{2})] \end{aligned}\right\}. \tag{22}$$

Substituting (22) into (11)-(13) and using the orthogonality condition with the eigen functions on the resulting equations, we get the following algebraic equations:

$$\begin{aligned} 2a_1\nu_c\left[F_1\left(\nu_c^3+\frac{\mu_1^4}{\nu_c}\right)+2F_2\nu_c\mu_1^2\right]A - 2a_1^2F_3\nu_c Ra_{nl}B&\\ +2\pi a_1F_4\sqrt{Ta}D = 0&, \end{aligned} \tag{23}$$

$$A\frac{(F_5C+2F_3)\nu_c}{a_1\delta_c^2} - B = 0, \tag{24}$$

$$AB + \frac{8a_1\pi^2}{F_5\nu_c}C = 0, \tag{25}$$

$$2\pi F_4\sqrt{Ta}A - \frac{\left[-6\nu_c^2+\pi^2(6+\delta_c^2)\right]}{12\pi^2}D = 0. \tag{26}$$

where F_1, F_2, F_3, F_4 are given by (18)-(21) and

$$F_5 = \frac{16\pi^2\mu_1^2\left(\mu_1^4+39\pi^4\right)}{\mu_1^8 - 82\pi^4\mu_1^4 + 81\pi^8}. \tag{27}$$

Solving (23)-(26), we get

$$A^2 = \frac{8\pi^2\delta_c^2 a_1^2 r}{\nu_c^2 F_5^2}\left[1-\frac{1}{r}\right], \quad (28)$$

$$B = \frac{2\nu_c F_3}{a_1\delta_c^2 r}A, \quad (29)$$

$$C = -\frac{F_3F_5\nu_c^2}{4\pi^2 a_1^2\delta_c^2 r}A^2 = -\frac{2F_3}{F_5}\left[1-\frac{1}{r}\right], \quad (30)$$

$$D = \frac{24\pi^3 F_4\sqrt{Ta}}{-6\nu_c^2+\pi^2(6+\delta_c^2)}A, \quad (31)$$

where

$$r = \frac{Ra_{nl}}{Ra_{nlc}} \quad (32)$$

is the scaled Rayleigh number.
We next study the heat transport in terms of Nusselt number.

D. Nusselt Number

The amount of heat transport by Rayleigh-Bénard-Taylor convection for rigid-rigid, isothermal boundaries can be quantified in terms of the Nusselt number, Nu_{nl}, as follows:

$$Nu_{nl} = \frac{\text{Heat transport by(conduction + convection)}}{\text{Heat transport by conduction}}.$$

Using Fourier first law and further simplyfying, we get:

$$Nu_{nl} = 1 + \frac{k_{nl}}{k_l}\left[\frac{-\int_0^{\frac{2\pi}{\nu}}\left(\frac{\partial\Theta}{\partial Z}\right)dX}{-\int_0^{\frac{2\pi}{\nu}}\left(\frac{d\Theta_b}{dZ}\right)dX}\right]_{Z=-\frac{1}{2}}, \quad (33)$$

where k_{nl} *and* k_l are the thermal conductivities of the nanoliquid and base liquid respectively.

Substituting dimensionless form of (9) and (22) in (33) and completing the integration, we get

$$Nu_{nl} = 1 - 2\pi\,\frac{k_{nl}}{k_l}\,C. \quad (34)$$

Using (30), (33) takes the form

$$Nu_{nl} = 1 + 2\frac{2\pi F_3}{F_5}\,\frac{k_{nl}}{k_l}\,\left[1-\frac{1}{r}\right],$$

where F_3, F_5 are given by (20) and (27) and r is given by (32).

II. Conclusion

From Tables I and II it is found that the thermophysical properties of the base liquid, nanoliquid and nanoparticles vary as shown below:

$a)$ $k_l < k_{nl} << k_{np}$,

$b)$ $(C_p)_{np} > (C_p)_l > (C_p)_{nl}$,

$c)$ $\rho_{np} > \rho_{nl} > \rho_l$,

TABLE I
Thermo-Physical Properties of Ethylene Glycol and Copper Nanoparticles at 300K [18]

Quantity	Ethylene Glycol	Copper nanoparticles
Density $[kg.m^{-3}]$	ρ_l=1114.4	ρ_{np}=8933
Specific heat $[J/kg-K]$	$(C_p)_l$=2415	$(C_p)_{np}$=385
Thermal conductvity $[W/m-K]$	k_l=0.252	k_{np}=401
Thermal expansion coefficient $[K^{-1}\times 10^5]$	β_l=65	β_{np}=1.67
Dynamic coefficient of viscosity $[kg/m-s]$	μ_l=0.0157	-
Thermal diffusivity $[m^2.s^{-1}\times 10^7]$	α_l=0.93636	α_{np}=1165.9

TABLE II
Thermo-Physical Properties of Ethylene Glycol-Copper Nanoliquid at 300K for Volume Fraction, $\chi = 0.1$ [18]

Quantity	Ethylene glycol-Copper
Density $(\rho_{nl})[kg.m^{-3}]$	1896.26
Specific heat $(C_p)_{nl}[J/kg-K]$	1458.70
Thermal conductvity $(k_{nl})[W/m-K]$	0.335824
Thermal expansion coefficient $(\beta_{nl})[K^{-1}\times 10^5]$	35.1662
Dynamic coefficient of viscosity $(\mu_{nl})[kg/m-s]$	0.020431
Thermal diffusivity $(\alpha_{nl})[m^2.s^{-1}\times 10^7]$	1.21408
$(\rho C_p)_{nl}$ $[J/m^3-K\times 10^{-6}]$	2.76607
$(\rho\beta)_{nl}$ $[kg/m^3-K]$	0.666842

$d)$ $\beta_l > \beta_{nl} > \beta_{np}$,

$e)$ $\alpha_{np} >> \alpha_{nl} > \alpha_l$.

To study the implications of linear stablity results, we may write Ra as:

$$Ra_{nl} = F Ra_l,$$

where
$F = \left[\frac{(\rho\beta)_{nl}}{\rho_l\beta_l}\frac{\mu_l}{\mu_{nl}}\frac{\alpha_l}{\alpha_{nl}}\right]$ and $Ra_l = \frac{\rho_l\beta_l g h^3\Delta T}{\mu_l\alpha_l}$.

On further computation it is seen that the factor, F, multiplying Ra_l decreases with increase in χ. This leads to the conclusion that the critical value of nanoliquid Rayleigh number is less than that of the base liquid without nanoparticles.

Rotation delays the onset of convection and thereby decreases heat transport. This result is shown in Fig. 2. This is because the energy of the system is used to create the component V.

The amount of heat transport increases with increase in χ and this is depicted in Fig. 3. Increase in the value of χ implies increase in volume fraction of nanoparticles.

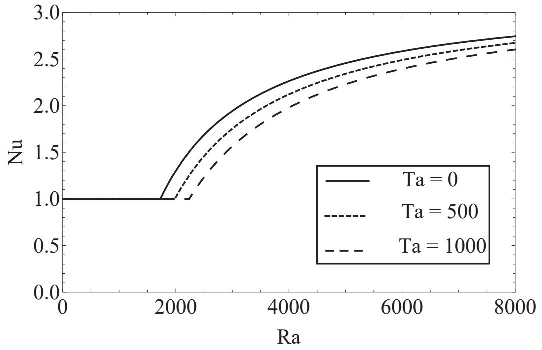

Fig. 2 Variation of Nu with Ra for different values of Ta, for χ=0.1

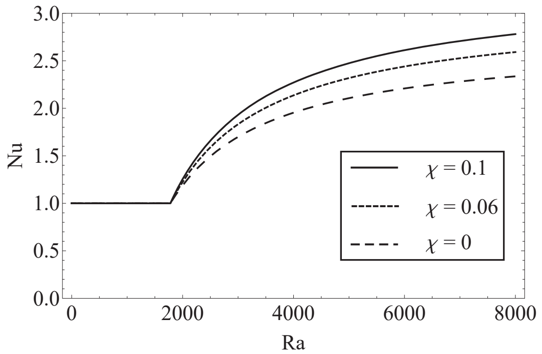

Fig. 3 Variation of Nu with Ra for different values of χ, for Ta=100

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