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G-Jitter Effects on Transient Natural Convection Couette Flow in a Vertical Channel with Convective Boundary Condition

Ponnan Bako
Department of Mathematics and Statistics, Plateau state polytechnic barkinladi-Nigeria
E-mail: ponnanbako@rocketmail.com
Abiodun O.Ajibade
Department of Mathematics, Ahmadu Bello University, Zaria-Nigeria
E-mail: aoajibade@abu.edu.ng

ABSTRACT

This article investigates the effects of g-jitter on transient natural convection Couette flow in a vertical channel. Fully developed laminar time dependent flow is considered. The flow formation is caused by the buoyancy force arising from the temperature gradient as a result of asymmetric heating of parallel plates as well as constant motion of one of the plates. The method of Laplace transforms is used to obtain the expressions for temperature and velocity which are used to compute the Nusselt number, skin-friction, mass flux and Mean temperature in Laplace domain then the Riemann-sum approximation is used to invert our expressions from Laplace domain to time domain. During the course of investigation, it was found that the influence of heat generation/absorption parameter on the rate of heat transfer on one plate is the reverse of the influence on the other plate. Increase in convective coefficients of the bounding plates constitute an enhancement to heat transfer, skin friction, mass flux as well as mean temperature within the channel

Keywords -Vertical channel, Natural convection, Couette flow, g-jitter, Convective B.C.

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I. INTRODUCTION

Many researchers investigated g-jitter convective flow in various aspects; see for example, Chen and Saghir[1]. The g-jitter induced flows in microgravity under the influence of a transverse magnetic field between two parallel plates have been analyzed by Li [2]. In his analysis, a single component of time harmonic g-jitter was taken into account. General solutions were obtained for the velocity profile with combined effect of oscillating g-jitter driving force and induced Lorentz force. He observed that the g-jitter frequency affects the convective flow. Chen and Chen [3] investigated the nature of instability occurring in a differentially heated vertical slot under a modified gravity field (g-jitter). They concluded that gravity modulation can stabilize or destabilize the flow. Farooq and Homsy[4] investigated streaming in a square cavity where a lateral temperature gradient interacts with a constant gravity field modulated by small harmonic oscillations. They found that under certain parametric conditionswith finite frequency and moderate Pr number, the periodic motion interacts with the instabilities associated with the base flow and causes resonances, which increases in strength as Ra increases. At low frequencies thestreaming flow shows marked structural changes as Ra increases. Farooq and Homsy [5] studied the dynamics of a differentially-heated, gravity-modulated slot and observed parametric resonance, which leads toinstability of the flow. The stability boundary was found to depend on the frequency and the amplitude of the modulation. Amin [6] investigated the heat transfer from a sphere immersed in an infinite viscous and incompressible fluid in a zero gravity environment under the influence of g-jitter. She has shown that heat transfer is negligibly small for high-frequency g-jitter but under special circumstances, when the Prandtl number is sufficiently high, low-frequency g-jitter may play an important role. Li and Shu [7] carried out a numerical study on double diffusive convection driven by g-jitter in a microgravity environment. They found that an increase of g-jitter force (amplitude) may cause the non-linear convective effects become much more obvious, which is drastically change the concentration field. In a related work, Shu*et al*[8] extended their previous work by incorporating external magnetic field. They used a finite element method for computation. The g-jitter effects on viscous fluid flow and porous medium have also been investigated by Rees and Pop [9]. Deka and Soundalgekar[10] have studied gravity modulation effect on transient free convection flow past an infinite vertical isothermal plate. They observed that transient velocity decreases with increasing frequency of gravity modulation or Prandtl number, but increases with increasing time. Sharidan*et al.* [11] studied g-jitter free convection flow in the stagnation-point region of a three- dimensional body. Saini et al [12] have studied the effect of gravity fluctuation on free convection flow past a uniformly moving infinite vertical porous maintained at a fluctuating temperature in a porous medium. They found that gravity modulation affects the skin friction and heat transfer coefficients considerably. Wasu and Rajvanshi[13] studied unsteady mixed convection flow under the influence of gravity modulation and magnetic field. The gravity modulation and magnetic field effect on the unsteady mixed convection flow subject to the influence of internal heating and time-periodic gravity modulation effect on thermal instability in a packed anisotropic porous medium was investigated by Bhadauria *et al.* [14].The gravity modulation effects on the free convective flow of elastico-viscous fluid were studied by Dey[15].

Because of the occurrence in a variety of engineering operations the boundary layer flow and heat transfer over a stretching surface has gained much importance. A few applications in the field of chemical engineering and metallurgy include extrusion of polymers, production of paper and so forth. The final product's quality massively depends on heat transfer rate between the fluid and stretching surface during the operation of heating and/or cooling. Consequently, most suitable heating and/or cooling fluid must be chosen as it has immense influence on the heat transfer rate. The physical importance of heat transfer over a moving surface has compelled many researchers to report their findings on this topic. The convective heat transfer is of excessive significance in procedures, in which high temperatures are involved for instance, gas turbines, nuclear plants, storage of thermal energy etc. Referring to numerous industrial and engineering processes, the convective boundary conditions are more practical including material drying, transpiration cooling process etc. Due to the practical importance of convective boundary conditions several researchers have studied and reported results on this topic for viscous fluid. Bataller[16] investigated the Blasius and Sakiadis flows in a viscous fluid with convective boundary conditions.it is found that the combined effects of increasing the Eckert number, the Prandtl number and the radiation parameter tend to reduce the thermal boundary layer thickness along the plate which as a result yields a reduction in the fluid temperature. The heat transfer of a viscous fluid over a stretching/shrinking sheet with convective boundary conditions has been studied by Yao *et al.* [17].It is found that the unsteady parameter reduces the thickness of the thermal boundary layer. Hammad *et al.* [18] discussed the radiation effects and effects of the thermal convective boundary condition, variable viscosity and thermal conductivity on coupled heat and mass transfer with mixed convection.it is found that the influence of the Prandtl number was to decrease the temperature field and hence decreased the thermal boundary layer while it increased for the magnetic parameter and the generalized Biot number. Vajravelu *et al.* [19]presented solution to the unsteady convective boundary layer flow of a viscous fluid over a vertical stretching surface with thermal radiation.

One of the basic flows in fluid mechanics is the Couette flow where the fluid motion is induced by movement of the bounding surface. The flow of a viscous incompressible fluid past an impulsively started horizontal flat plate was first studied by Stokes [20].Singh and Kumar [21] investigated the formation of Couette flow of a viscous, incompressible and electrically conducting fluid between two infinite parallel plane walls in the presence of transverse magnetic field, by assuming that the magnetic lines of force are fixed relative to the moving plate for both the impulsive and accelerated motion of the moving plates and came out with the deduction that magnetic field increases the velocity field in both cases. However, very few papers deal with free convection in Couette motion between vertical parallel plates. The effect of natural convection on unsteady Couette flow was studied by Singh [22] .The Laplace transform technique was used to obtain the velocity and temperature fields, the skin-friction and rate of heat transfer. It was observed that an increase in the Grashof number results in an increase in the flow velocity. Jha[23] extended the work of Singh [22] by discussing the combined effects of natural convection and a uniform transverse magnetic field when the magnetic field is fixed relative to the plate or fluid. Using the Laplace transform technique, exact solutions were obtained for the velocity and temperature fields. The trends observed with respect to the magnetic parameter were consistent with those observed in Rossow[24]. Singh et al. [25] examined the effect of rotation on the unsteady hydromagnetic Couette flow when one of the plates has been set into accelerated motion; they noticed a decrease in velocity due to rotation and an increase due to magnetic field. Fully-developed laminar free convection Couette flow between two vertical parallel plates with transverse sinusoidal injection of the fluid at the stationary plate and its corresponding removal by constant suction through the plate in uniform motion has been analyzed by Jain and Gupta [26]. The physical effect of external shear in the form of Couette flow of a Bingham fluid in a vertical parallel plane channel with constant temperature differential across the walls was investigated analytically by Barletta and Magyari[27] Steady fully-developed combined forced and free convection Couette flow with viscous dissipation in a vertical channel has been investigated analytically by Barletta *et al.* [28].In this study, the moving wall is thermally insulated and the wall at rest is kept at a uniform temperature. The natural convection in unsteady Couette flow of a viscous incompressible fluid confined between two vertical parallel plates in the presence of thermal radiation has been studied by Narahari[29].

2. MATHEMATICAL ANALYSIS

Transient natural Convection flow of a viscous incompressible heat generating/absorbing fluid is considered in a vertical channel bounded by two infinite parallel plates. The flow is assumed to be in $x'-$direction which is taken vertically along one of the plates while $y'-$axis is taken normal to it. The second plate is placed h distance away from the first. At time$t' \leq 0$, the fluid is at rest, the temperature of fluid and that of the channel plates are kept at T_0. At time $t' > 0$, the temperature of the plates $y' = 0$ raised or fell to T_w and thereafter maintained constant while the other plate $y' = h$ remains at T_0. Also, the plate $y' = 0$ moves in its own plane impulsively at a uniform velocity u'=U while the other

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plate remains at rest, the acceleration due to gravity is assumed to fluctuate sinusoidally with t , amplitude ε and frequency ω.The flow configuration and coordinates system is shown in ***figure1 below***

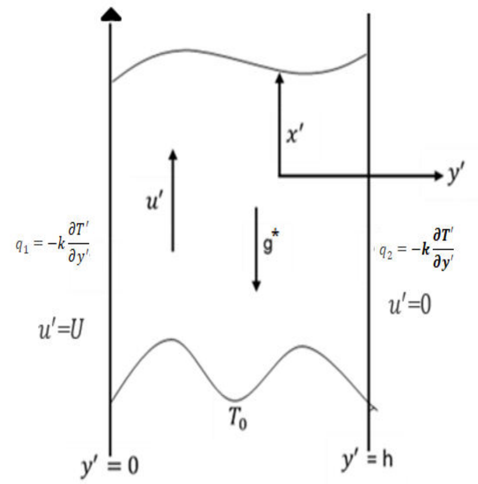

Figure1: Schematic diagram of the flow

Where $q_1 = -k\frac{\partial T'}{\partial y'} = H_1(T_w - T')$ and $q_2 = -k\frac{\partial T'}{\partial y'} = H_2(T' - T_0)$ defined in equation 4 bellow

Note that the g-jitter is fluctuating with amplitude ϵ and frequency ω and also as the amplitude approaches zero, the acceleration due to gravity becomes constant so that the problem coincides with the work of Jha and Ajibade[30].

Then under the usual Boussinesq's approximation the flow is shown to be governed by the following system of equations:

$$\frac{\partial u'}{\partial t'} = \nu\frac{\partial^2 u'}{\partial y'^2} + g^* \beta\,(T' - T_0)(1)$$

$$\frac{\partial T'}{\partial t'} = \frac{K}{\rho\, C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{Q_0\,(T' - T_0)}{\rho\, C_p}(2)$$

Where acceleration due to gravity is given **as** $g^* = g\left(1 + \epsilon \sin \omega' t'\right)$ **Ramos** [31].

with the initial condition

$$u'\,(0,\, y) = T'\,(0, y) = 0\;(3)$$

And the boundary conditions as: $t >$

$$0: \begin{cases} u'(t,\, 0) = U & q_1 = -k\frac{\partial T'}{\partial y'} = H_1(T_w - T') \\ u'(t, h) = 0 & q_2 = -k\frac{\partial T'}{\partial y'} = H_2(T' - T_0) \end{cases} \quad (4)$$

In other to solve the governing equations in dimensionless form, we introduce the following non-dimensional quantities:

$$y = \frac{y'}{h}\quad,\quad t = \frac{t'\nu}{h^2}, u = \frac{u'}{U},\quad \theta = \frac{T' - T_0}{T_w - T_0}, \omega = \frac{\omega' h^2}{\nu},$$

$$\delta = \frac{Q_0\, h^2}{k}\;, Pr = \frac{\mu\, C_p}{k}, Gr = \frac{g\beta h^2\,(T_w - T_0)}{\nu U},\quad (5)$$

Pr is the Prandtl number which is inversely proportional to the thermal diffusivity of the working fluid, $\boldsymbol{\delta}$ is the heat generation/absorption parameter, positive values denote absorption while negative values denote heat generation, Gr is the Grashof number. The physical quantities used in eq. (5) are defined in the nomenclature.

Upon substitution of equation (5) in to (1)-(4), the following equations are rendered in dimensionless form as:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\;\; \theta\left(1 + \epsilon\, Sin\;\omega t\right)\quad (6)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} - \frac{\delta}{Pr}\theta \quad (7)$$

$$u(0,\, y) = \theta\,(0, y) = 0 \quad (8)$$

With boundary conditions in dimensionless form as:

$$t > 0: \begin{cases} u(t, 0) = 1, & \frac{\partial \theta}{\partial y} = B_{i_1}(\theta - 1) \\ u(t, 1) = 0 & \frac{\partial \theta}{\partial y} = -B_{i_2}\theta \end{cases} \quad (9)$$

Where $B_{i_1} = \frac{H_1 h}{K}$ **and** $B_{i_2} = \frac{H_2 h}{K}$ are the Biot numbers on the plates respectively.
Introducing the Laplace transformations which are:

$$L\big(u(t, y)\big) = \overleftrightarrow{u}(s, y) = \int_0^\infty u exp(-st)dt \quad \textbf{(10)}$$

$$L\big(\theta(t, y)\big) = \overleftrightarrow{\theta}(s, y) = \int_0^\infty \theta exp(-st)dt \quad \textbf{(11)}$$

$$L(\theta(t, y)exp(i\omega t)) = \overleftrightarrow{\theta}(p, y) = \int_0^\infty \theta exp(-pt)dt \quad \textbf{(12)}$$

$$L(\theta(t, y)exp(-i\omega t)) = \overleftrightarrow{\theta}(q, y) = \int_0^\infty \theta exp(-qt)dt \quad \textbf{(13)}$$

(where s, p, q are the Laplace parameters such that $s > 0, p > 0, q > 0$) then applying the properties of Laplace transformation above on equation (6) and (7) gives:

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$$\frac{d^2\overleftrightarrow{U}(\mathrm{s,y})}{dy^2} - s\overleftrightarrow{u}(\mathrm{s,y}) = -Gr(\overleftrightarrow{\theta}(s,y) + \frac{\epsilon}{2i}(\overleftrightarrow{\theta}(p,y) - \overleftrightarrow{\theta}(q,y))) \qquad (14)$$

$$A\frac{d^2\overleftrightarrow{\theta}(\mathrm{s,y})}{dy^2} - s\overleftrightarrow{\theta}(\mathrm{s,y}) = B\overleftrightarrow{\theta}(\mathrm{s,y}) \quad (15)$$

Where A,B,p and q are defined in the Appendix

Boundary conditions as:

$$s > 0: \begin{cases} \overleftrightarrow{U}(s,0) = \frac{1}{s} \quad , \frac{d\overleftrightarrow{\theta}}{dy} = B_{i_1}(\overleftrightarrow{\theta} - \frac{1}{s}) \\ \overleftrightarrow{U}(s,1) = 0 \ , \ \frac{d\overleftrightarrow{\theta}}{dy} = -B_{i_2}\overleftrightarrow{\theta} \end{cases} \quad (16)$$

The solution of equation (14) and (15) under the boundary conditions (16) in Laplace domain is given as:

$$\overleftrightarrow{\theta} = C_5\, exp(my) + C_6\, exp(-my) \quad (17)$$

$$\overleftrightarrow{u} = C_{31}\, exp(m^p y) + C_{41}\, exp(-m^p y) + a_{01} exp(my) + a_{11} exp(-my) + a_{21} exp(m_1 y) + a_{31} exp(-m_1 y) + a_{41} exp(m_2 y) + a_{51} exp(-m_2 y) \quad (18)$$

Where C_{31}, C_{41}, a_{01}, a_{11}, a_{21}, a_{31}, a_{41}, a_{51}, C_5 and C_6 are defined in the Appendix.

Using the expressions (17) and (18), the rate of heat transfer from plate to fluid which is the Nusselt number, the shear stress on the boundary surface called the volumetric flow rate also known as skin-friction, mass flux and Mean temperature can be given in Laplace domain respectively as

Nusselt number

$$\overleftrightarrow{Nu} = \frac{d\overleftrightarrow{\theta}}{dy} = mc_5 exp(my) - mc_6 exp(-my) \quad (19)$$

So that when $y = 0$ the Nusselt number becomes

$$\overleftrightarrow{\mathrm{N}}u_0 = \left.\frac{d\overleftrightarrow{\theta}}{dy}\right|_{y=0} = mc_5 - mc_6 \quad (20)$$

And also on the surface of the cold plate (i.e. when $y = 1$) Nusselt number becomes

$$\overleftrightarrow{\mathrm{N}}u_1 = \left.\frac{d\overleftrightarrow{\theta}}{dy}\right|_{y=1} = mc_5 exp(m) - mc_6 exp(-m) \quad (21)$$

Skin-friction

$$\overleftrightarrow{\tau} = \frac{d\overleftrightarrow{u}}{dy} = C_{31}\, m^p exp(m^p y) - C_{41}\, m^p exp(-m^p y) + a_{01} m exp(my) - a_{11} m exp(-my) + a_{21} m_1 exp(m_1 y) - a_{31} m_1 exp(-m_1 y) + a_{41} m_2 exp(m_2 y) - a_{51} m_2 exp(-m_2 y) \quad (22)$$

So that when $y = 0$ the skin-friction becomes

$$\overleftrightarrow{\tau}_0 = \left.\frac{d\overleftrightarrow{u}}{dy}\right|_{y=0} = C_{31}\, m^p - C_{41}\, m^p + a_{01} m - a_{11} m + a_{21} m_1 - a_{31} m_1 + a_{41} m_2 - a_{51} m_2 \quad (23)$$

And also on the surface of the cold plate (i.e. when $y = 1$) the Skin friction becomes

$$\overleftrightarrow{\tau}_1 = \left.\frac{d\overleftrightarrow{u}}{dy}\right|_{y=1} = C_{31}\, m^p exp(m^p) - C_{41}\, m^p exp(-m^p) + a_{01} mexmexp(-m) + a_{21} m_1 exp(m_1) - a_{31} m_1 exp(-m_1) + a_{41} m_2 exp(m_2) - a_{51} m_2 exp(-m_2) \quad (24)$$

Mass flux

The mass flux within the channel is also an important phenomenon that needs to be investigated. This is done by evaluating the sum total of fluid velocity over the entire flow domain

$$\overleftrightarrow{Q} = \int_0^1 \overleftrightarrow{u}\, dy = \frac{C_{31}}{m^p}(exp(m^p) - 1) - \frac{C_{41}}{m^p}(exp(-m^p) - 1) + \frac{a_{01}}{m}(exp(m) - 1) - \frac{a_{11}}{m}(exp(-m) - 1) + \frac{a_{21}}{m_1}(exp(m_1) - 1) - \frac{a_{31}}{m_1}(exp(-m_1) - 1) + \frac{a_{41}}{m_2}(exp(m_2) - 1) - \frac{a_{51}}{m_2}(exp(-m_2) - 1) \quad (25)$$

Mean temperature

The average temperature within the flow domain is given by the quotient of the bulk temperature and the mass flux

$$\overleftrightarrow{\theta}_m = \frac{\int_0^1 \overleftrightarrow{U}\overleftrightarrow{\theta} dy}{\int_0^1 \overleftrightarrow{U} dy} \quad (26)$$

$$\int_0^1 \overleftrightarrow{U}\overleftrightarrow{\theta} dy = \overleftrightarrow{\theta}_b = \frac{C_5\, C_{31}}{m+m^p}(exp(m + m^p) - 1) + \frac{C_5\, C_{41}}{m-m^p}(exp(m - m^p) - 1) + \frac{C_5\, a_{01}}{2m}(exp(2m) - 1) + a_{11}\, C_5 + \frac{C_5\, a_{21}}{m_1+m}(exp(m_1 + m) - 1) + \frac{C_5\, a_{31}}{m-m_1}(exp(m - m_1) - 1) + \frac{C_5\, a_{41}}{m_2+m}(exp(m_2 + m) - 1) + \frac{C_5\, a_{51}}{m-m_2}(exp(m - m_2) - 1) + \frac{C_6\, C_{31}}{m^p-m}(exp(m^p - m) - 1) - \frac{C_6\, C_{41}}{m+m^p}\big(exp(-(m + m^p)) - 1\big) + a_{01}\, C_6 - \frac{C_6\, a_{11}}{2m}(exp(-2m) - 1) + \frac{a_{21}\, C_6}{m_1-m}(exp(m_1 - m) - 1) - \frac{a_{31}\, C_6}{m_1+m}(exp(-(m_1 + m)) - 1) + \frac{a_{41}\, C_6}{m_2-m} exp(m_2 - m) - 1) - \frac{C_6\, a_{51}}{m_2+m} exp(-(m_2 + m)) - 1) \quad (27)$$

Since we know that $\vec{Q} = \int_0^1 \vec{u}\, dy$ in equation (25) then Mean temperature can be represented in Laplace domain as

$$\overleftrightarrow{\theta}_m = \frac{\int_0^1 \vec{U}\vec{\theta} dy}{\int_0^1 \vec{U} dy} = \frac{\vec{\theta}_b}{\vec{Q}} \qquad (28)$$

3. RESULTS AND DISCUSSION

An unsteady free convective Couette flow of viscous incompressible fluid is considered in a vertical channel formed by two infinite vertical parallel plates. The plates are subjected to asymmetric thermal conditions and one of the plates moves impulsively with uniform velocity in its own plane. The objective of the present work is to investigate the influence of Grashof number (Gr), Prandtl number (Pr), g-jitter (g^*) and heat generation/absorption (δ) on fluid temperature, fluid velocity, rate of heat transfer, Nusselt number and skin-friction on the boundary plates. The values of the Prandtl number are taken to be 0.71 (Prandtl number of air), 7.0 (Prandtl number of water), 2.0 (Prandtl number of sulphur dioxide), 3.0 (Prandtl number of liquid freon). The Grashof number which depends on the plate's thermal status takes positive, zero and negative values depending on the temperature difference between the plates, while in our work we arbitrarily take the values of the Grashof number to be 18, 45 and 89. The values of heat generation/absorption are taken in our work within the range of ($-4 \le \delta \le 4$) and time also is taken within the range of ($0.1 \le t \le 0.7$), the amplitude of the fluctuating acceleration due to gravity is taken to be less than unity ($\epsilon < 1$) and also the oscillating frequency (ω) is taken arbitrarily as $\frac{\pi}{18}, \frac{\pi}{3}, \frac{11\pi}{18}, \frac{17\pi}{18}$.

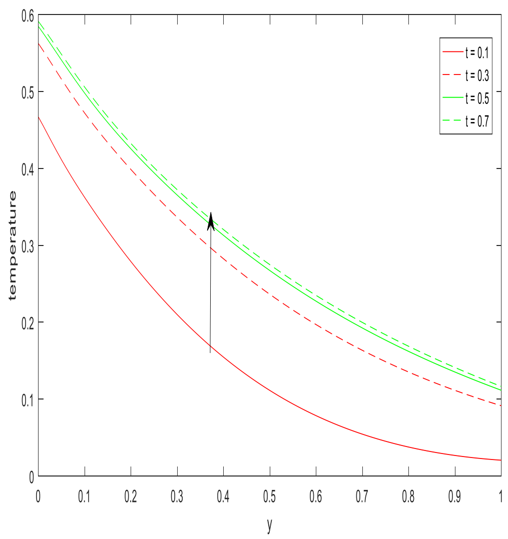

Figure2: Temperature profile for different values of time (Pr=0.71, $\delta = 2, B_{i_1} = B_{i_2} = 2$)

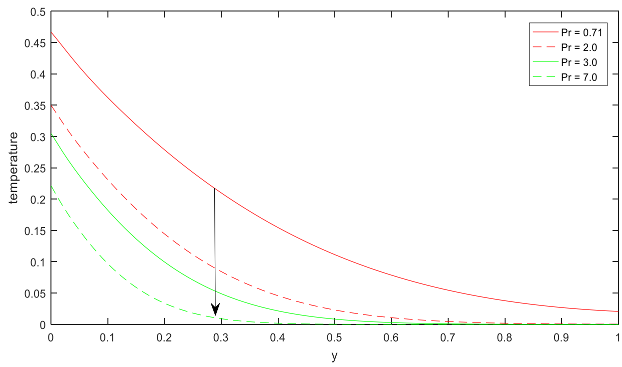

Figure3: Temperature profile for different values of diffusivity ($t = 0.1, \delta = 2, B_{i_1} = B_{i_2} = 2$)

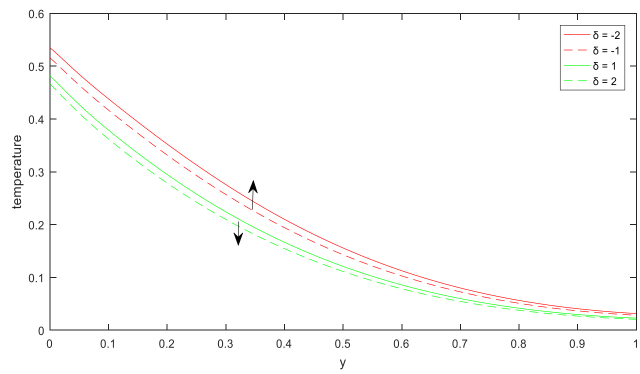

Figure4:Temperature profile for different values of heat generation/absorption(Pr=0.71 and t=0.1, $B_{i_1} = B_{i_2} = 2$)

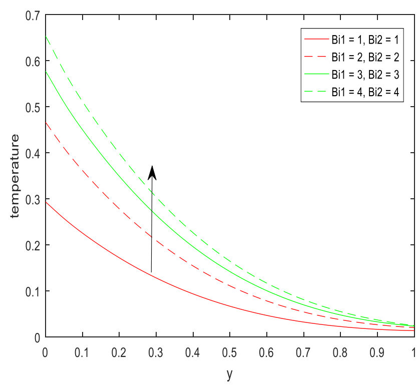

Figure5: Temperature profile for variation of Biot number (Pr=0.71, t=0.1, δ =2)

Figure2 to 5 show the effect of the various parameters on the temperature profile when the thermal boundary condition is been made convective. Figure2 presents that as the time increases, there is an increase in the fluid temperature,it was further observed that the influence of boundary convection on the temperature decreases with growing time. Figure3 illustrates that as the thermal diffusivity decreases, there is a decrease in the fluid temperature within the flow domain. However the effect of boundary convection is much felt on the heated plate

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while it is negligible on the cold plate. This could be attributed to decrease in thermal diffusivity of the fluids with growing Pr which act against heat penetration through different fluid layers so that a greater percentage of heat from the boundary heating are lost to the ambience through the boundary convection. Figure4 presents that as the heat absorption increases within the channel, there is a decrease in the fluid temperature within the channel, and also as the heat generation increases, there is an increase in the fluid temperature at the heated and cold plate. Figure5 depicts that increase in the Biot number increases the temperature of the fluid in the flow domain. This is due to the physical fact that an increase in Biot number constitute an increase in temperature flux through the boundary plates to the fluid.

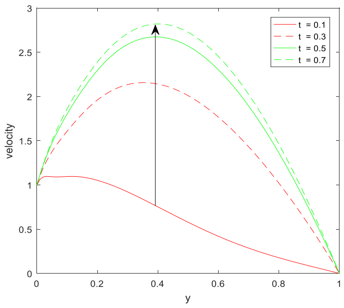

Figure6: Velocity profile for different time(Gr=45, Pr=0.71, $\omega=\frac{\pi}{18}$, ϵ =0.9, δ =2, $B_{i_1} = B_{i_2} = 2$)

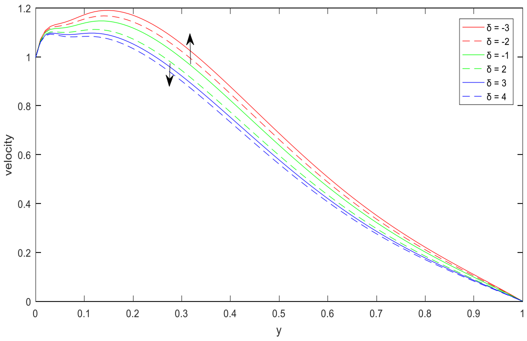

Figure7: Velocity profile for different heat generation/absorption (Gr=45, Pr=0.71, $\omega=\frac{\pi}{18}$, ϵ =0.9, t =0.1, $B_{i_1} = B_{i_2} = 2$)

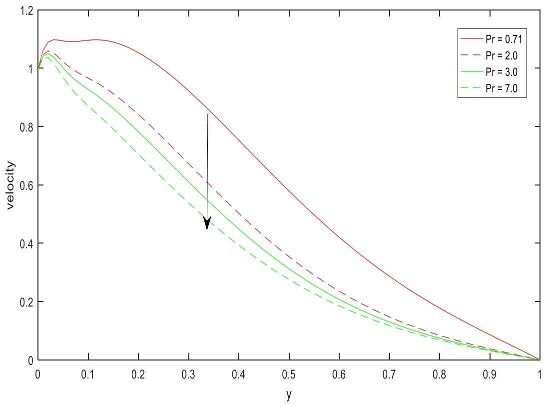

Figure8: Velocity profile for different fluid diffusivity (Gr=45, δ =2, $\omega=\frac{\pi}{18}$, ϵ =0.9, t =0.1, $B_{i_1} = B_{i_2} = 2$)

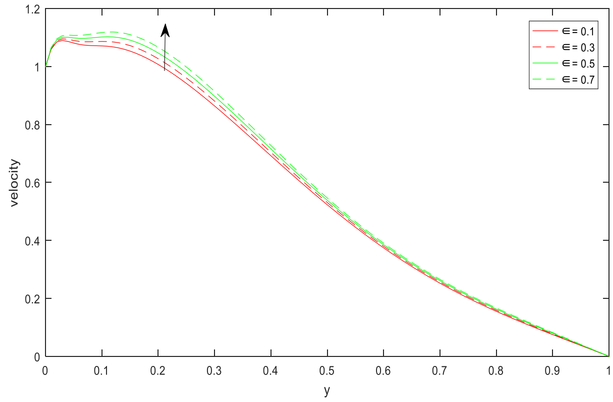

Figure9: Velocity profile for different amplitude(Gr=45, $\omega=\frac{17\pi}{18}$, $\mathrm{Pr} = 0.71$, δ =2, t =0.1, $B_{i_1} = B_{i_2} = 2$)

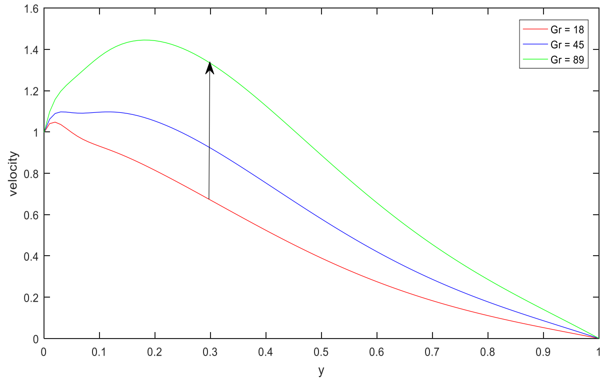

Figure10: Velocity profile for different convection current(Pr=0.71, δ =2, $\epsilon = 0.9$, $\omega=\frac{\pi}{18}$, δ =2, t =0.1, $B_{i_1} = B_{i_2} = 2$)

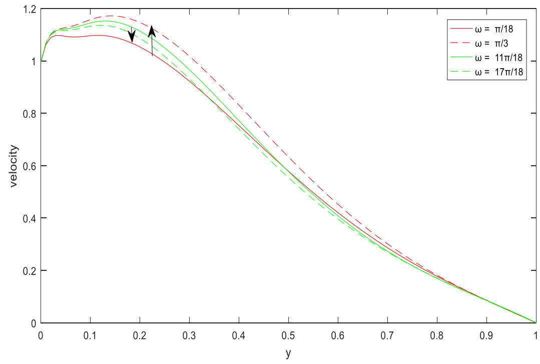

Figure11: Velocity profile for different oscillating frequency (Pr=0.71, $\epsilon = 0.9$, Gr=45, δ =2, t =0.1, $B_{i_1} = B_{i_2} = 2$)

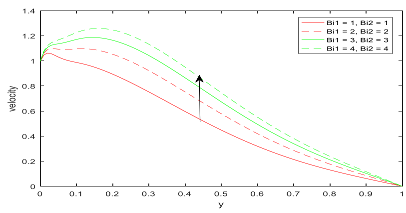

Figure12: Velocity profile for variation of Biot number (Pr=0.71, $\epsilon = 0.9$, Gr=45, δ =2, t =0.1, $\omega=\frac{\pi}{18}$)

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Figure6 to 12 illustrate the effect of the governing parameters on the velocity profile when the thermal boundary condition is being made convective. Figure6 illustrates that as the time increases, the velocity of the fluid increases. This is the hydrodynamic response to temperature increase with growing time which has been observed in Figure2. Consequent upon the temperature increase, convection current is strengthened and the fluid buoyancy is enhanced and increasing fluid velocity results. Figure7 presents thatas the heat absorption increases there is a resultant decrease in fluid velocity, however in the presence of heat generation, fluid velocity increases with growing heat generation. This is physically true since heat generation causes an increase in fluid temperature while heat absorption decreases it. Hence, the direct consequent of these fluid properties on the convection current is what brings about the observed velocity response to thermal generation and absorption. Figure8 presents that as the thermal diffusivity decreases, the fluid velocity decreases in the flow domain. Figure9 shows that as the amplitude of the g-jitter increases, the velocity of the fluid within the channel increases. Figure10 illustrates that as the convection current increases, the velocity of the fluid within the channel increases. The effect of frequency of modulation of g-jitter on the hydrodynamics within the channel is shown in Figure11; the figure reveals that as the oscillating frequency increases, there is a fluctuation about a Mean velocity. Figure12 illustrates that increase in the Biot number of the plates lead to an increase in the velocity of the fluid in the flow domain, this is due to the fact that increase in the Biot number increases the temperature in the flow domain and hence increases the velocity of the fluid in the flow domain.

Table1: The influences of Biot number,Pr, t and δ on the rate of heat transfer when pr=0.71 and t=0.1

		$pr = 0.71$,	$t = 0.1$
Biot number	δ	NU_0	NU_1
$B_{i_1} = 2$	-3	0.8831114	0.0703136
$B_{i_2} = 2$	-1	0.9629835	0.0567274
	1	1.0312980	0.0458732
	3	1.0900779	0.0371839
$B_{i_1} = 3$	-3	0.9725817	0.0920411
$B_{i_2} = 2$	-1	1.1003278	0.0743371
	1	1.2102454	0.0601801
	3	1.3054040	0.0488361
$B_{i_1} = 3$	-3	0.9726265	0.1203688
$B_{i_2} = 3$	-1	1.1003619	0.0973254
	1	1.2102716	0.0788811
	3	1.3054242	0.0640875

Table2: The influences of Biot number,Pr, t and δ on the rate of heat transfer when pr=2.0 and t=0.1

		$pr = 2.0$,	$t = 0.1$
Biot number	δ	NU_0	NU_1
$B_{i_1} = 2$	-3	1.2456586	0.0009130
$B_{i_2} = 2$	-1	1.2664740	0.0008359
	1	1.2861414	0.0007655
	3	1.3047363	0.0007012
$B_{i_1} = 3$	-3	1.5369654	0.0012774
$B_{i_2} = 2$	-1	1.5740553	0.0011697
	1	1.6091464	0.0010714
	3	1.6423772	0.0009815
$B_{i_1} = 3$	-3	1.5369654	0.0017871
$B_{i_2} = 3$	-1	1.5740532	0.0016367
	1	1.6091464	0.0014993
	3	1.6423772	0.0013737

Table3: The influences of Biot number,Pr, t and δ on the rate of heat transfer when pr=2.0 and t=0.3

		$pr = 2.0$,	$t = 0.3$
Biot number	δ	NU_0	NU_1
$B_{i_1} = 2$	-3	0.8558505	0.0833592
$B_{i_2} = 2$	-1	0.9425296	0.0664783
	1	1.0159324	0.0531622
	3	1.0785161	0.0426329
$B_{i_1} = 3$	-3	0.9328627	0.1085709
$B_{i_2} = 2$	-1	1.0704783	0.0866926
	1	1.1877737	0.0694163
	3	1.2884481	0.0557410
$B_{i_1} = 3$	-3	0.9329386	0.1412624
$B_{i_2} = 3$	-1	1.0705355	0.1129433
	1	1.1878171	0.0905564
	3	1.2884811	0.0728159

Table1 to Table3 shows the effect of varying Biot number on the rate of heat transfer in the flow domain. It was observed from the table that as the Biot number increases on both the plate, the rate of heat transfer also increases and as the Biot number of the heated plate increases while that of the cold plate remains constant, it was observed that the rate of heat transfer still increases on both the plate, this is true because an increase in the convective coefficient of the bounding plates brings about increase in the heat flux through the boundaries which results to increase in temperature of the fluid in the flow domain, hence increasing the rate of heat transfer on the plates.The table shows that heat transfer decreases on the heated plate and increases on the cold plate with growing heat generation while it increases on the heated plate and decreases on the cold plate withgrowing heat absorption. However, a decrease in the thermal diffusivity has been observed to increase the rate of heat transfer on the heated plate while it decreases it on the cold plate. This is attributed to the physical fact that a decrease in thermal diffusivity (increasing Pr) causes a decrease in fluid temperature which tends to increase the temperature difference between the hot plate and the fluid.

The effect of time increase on rate of heat transfer is also depicted on the table. It can be deduced that the rate of heat transfer becomes lowered with growing time on the heated surface and increases on the cold plate.

Table4: The influences of the governing parameters regarding the skin-friction (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 0.71, \omega = \frac{\pi}{18}$)

		$pr = 0.71$, $\omega = \frac{\pi}{18}$	
	δ	τ_0	τ_1
$t = 0.1$ $\epsilon = 0.5$	-3	10.759526	1.2847342
	-1	10.288967	1.1508084
	1	9.8803955	1.0385229
	3	9.5240292	0.9440281
$t = 0.3$ $\epsilon = 0.5$	-3	19.580787	12.984709
	-1	15.591415	9.1287036
	1	12.965722	6.7346422
	3	11.168262	5.1951061
$t = 0.3$ $\epsilon = 0.9$	-3	21.589358	15.593858
	-1	16.987681	10.786620
	1	13.970468	7.8275730
	3	11.914736	0.0728159

Table5: The influences of the governing parameters regarding the skin-friction (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 2.0$, $\omega = \frac{\pi}{18}$)

		$pr = 2.0$, $\omega = \frac{\pi}{18}$	
	δ	τ_0	τ_1
$t = 0.1$ $\epsilon = 0.5$	-3	8.1652814	0.3905224
	-1	8.0596408	0.3866264
	1	7.9596086	0.3829387
	3	7.8648336	0.3794461
$t = 0.3$ $\epsilon = 0.5$	-3	11.390515	3.9570262
	-1	10.521638	3.5432081
	1	9.7812698	3.1969443
	3	9.14729218	2.9060296
$t = 0.3$ $\epsilon = 0.9$	-3	12.481971	4.5443186
	-1	11.472843	4.0458044
	1	10.613920	3.6286923
	3	9.8793486	3.2783190

Table6: The influences of the governing parameters regarding the skin-friction (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 2.0$, $\omega = \frac{\pi}{3}$)

		$pr = 2.0$, $\omega = \frac{\pi}{3}$	
	δ	τ_0	τ_1
$t = 0.1$ $\epsilon = 0.5$	-3	8.4910499	0.4029548
	-1	8.3735569	0.3987392
	1	8.2622034	0.3947367
	3	8.1566113	0.3909344
$t = 0.3$ $\epsilon = 0.5$	-3	10.991701	3.5981677
	-1	10.226341	3.2337127
	1	9.5715312	2.9308830
	3	9.0082583	2.6781283
$t = 0.3$ $\epsilon = 0.9$	-3	11.764105	3.8983734
	-1	10.941309	3.4887123
	1	10.236391	3.1497820
	3	9.6290878	2.8680967

Table4 to Table 6 above shows that the skin-friction on the heated and cold plate increases as the heat generation grows, while heat absorption brought about decrease of the skin-friction on the heated and cold plate. And also as thermal diffusivity decreases (i.e. increasing Pr) it was observed that the skin-friction on the heated andcold plate decreases, this is attributed to the fact that decrease in thermal diffusivity lead to decrease in the temperature and velocity of the fluid and hence the skin-friction decreases on both the plates, the skin-friction on the heated plate is higher than that of the cold plate.

The effect of time, oscillating frequency of g-jitterand g-jitter amplitude is also depicted on the table and it was observed that as the time increases the skin-friction on the heated and cold plate also increases, and increasing the amplitude of the g-jitter brought about increase in the skin-friction of the heated and cold plate, reason been that, increase in the amplitude of the g-jitter lead to increase in the velocity and hence increases the skin-friction on both the plates. Increasing the g-jitter oscillating frequency brings about increase in the skin-friction on the heated and cold plate, it was also observed that the skin-friction increases on both the plate with growing time and g-jitter amplitude. It is interesting to note that the influence of oscillating frequency on skin friction is dependent on the time as an increase in ω causes the skin friction to increase on the heated plate when t is small. However the trend is being reversed as the time increases.

Table7: The influence of convection current in the flow domain skin-friction (t=0.1, $\omega = \frac{\pi}{18}$,Pr=0.71,$\delta = 2$,∈= 0.9,$B_{i_1} = B_{i_2} = 3$)

Gr	τ_0	τ_1
18	6.3569827	0.3317933
45	8.0625877	0.3900225
89	10.8420921	0.4849145

Table7 depicts the effect of varying convection current on the skin-friction in the flow domain .It was observed from the table above that as the convection current increases, the skin-friction on the heated and cold plate both increases, this is true because increase in the convection current brings about increase in the temperature and velocity of the fluid in the flow domain and hence increases the skin-friction of the heated and cold plate.

Table8: The mass flow rate and the average temperature in the flow domain for variation in governing parameters (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 2.0$ and $\omega = \frac{\pi}{3}$)

		$pr = 2.0$, $\omega = \frac{\pi}{3}$	
	δ	Q	θ_m
$t = 0.1$ $\epsilon = 0.5$	-3	0.7275855	0.0104049
	-1	0.6879938	0.0110289
	1	0.6538922	0.0101549
	3	0.6244047	0.0100064
$t = 0.3$ $\epsilon = 0.5$	-3	2.8071203	0.0387835
	-1	2.1585944	0.0388097
	1	1.7387707	0.0383438
	3	1.4573145	0.0374963
$t = 0.3$ $\epsilon = 0.9$	-3	3.2104055	0.0360771
	-1	2.4302730	0.0363743
	1	1.9281306	0.0362164
	3	1.5935755	0.0356779

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Table9: The mass flow rate and the average temperature in the flow domain for variation in governing parameters (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 2.0$ and $\omega = \frac{\pi}{18}$)

		$pr = 2.0$, $\omega = \frac{\pi}{18}$	
	δ	Q	θ_m
$t = 0.1$ $\epsilon = 0.5$	-3	0.4689321	0.0073242
	-1	0.4640041	0.0072209
	1	0.4593440	0.0071186
	3	0.4549352	0.0070175
$t = 0.3$ $\epsilon = 0.5$	-3	1.3387908	0.0255302
	-1	1.2348084	0.0254440
	1	1.1467798	0.0252918
	3	1.0719452	0.0250792
$t = 0.3$ $\epsilon = 0.9$	-3	1.4938598	0.0236007
	-1	1.3686978	0.0236303
	1	1.2628405	0.0235977
	3	1.1729469	0.0235060

Table10: The mass flow rate and the average temperature in the flow domain for variation in governing parameters (Gr=45,$B_{i_1} = B_{i_2} = 3, pr = 2.0$ and $\omega = \frac{\pi}{3}$)

		$pr = 2.0$, $\omega = \frac{\pi}{3}$	
	δ	Q	θ_m
$t = 0.1$ $\epsilon = 0.5$	-3	0.4854523	0.0071341
	-1	0.4799512	0.0070379
	1	0.4747397	0.0069427
	3	0.4698005	0.0068484
$t = 0.3$ $\epsilon = 0.5$	-3	1.2208131	0.0281701
	-1	1.1376187	0.0278207
	1	1.0669689	0.0274112
	3	1.0066881	0.0269521
$t = 0.3$ $\epsilon = 0.9$	-3	1.2815000	0.0278079
	-1	1.1937563	0.0274413
	1	1.1191808	0.0270172
	3	1.0554807	0.0265463

Table8 to Table 10 above shows the influence of the governing parameters on the mass flux and Mean temperature. It was observed that as the heat generation grows, the mass flux and the Mean temperature increases with decreasing thermal diffusivity while the opposite occur with growing heat absorption and the Mean temperature, when it is air (Pr=0.71) it decreases any ways. The mass flux and the Mean temperature grows with growing time, as thermal diffusivity decreases (i.e. increasing Pr) it was observed that the mass flux and Mean temperature also decreases. And also as the oscillating frequency of the g-jitter grows, the mass flux increases and Mean temperature decreases. And lastly as the amplitude of the g-jitter grows, it was observed that the mass flux increases and Mean temperature decreases.

Table11: Variation in convection current on mass flux and Mean temperature (t=0.1, $\omega = \frac{\pi}{18}$,Pr=0.71,$\delta = 2$,$\in = 0.9$,$B_{i_1} B_{i_2} = 3$)

Gr	Mass flux	mean temperature
18	0.4756118	0.0122466
45	0.6622992	0.0097886
49	0.9665303	0.0078176

Table11 above shows the effect of varying convection current on the mass flux and Mean temperature. It was observed from the table that as the convection current increases, the mass flux increases and the Mean temperature decreases, due to the fact that increase in the convection current lead to increase of the velocity of the fluid in the channel which increases the mass flux and decrease the Mean temperature of the fluid.

Table12: Effect of Biot number on the skin-friction(t=0.1, $\omega = \frac{\pi}{18}$,Pr=0.71,$\delta = 2$,$\in = 0.9$,Gr=45)

Biot number	τ_0	τ_1
$B_{i_1} = 1$ $B_{i_2} = 1$	7.48008029	0.63732665
$B_{i_1} = 2$ $B_{i_2} = 2$	8.91759583	0.88370256
$B_{i_1} = 3$ $B_{i_2} = 3$	9.89714602	1.06744811

Table13: Effect of Biot number on the mass flux and Mean temperature (t=0.1, $\omega = \frac{\pi}{18}$,Pr=0.71,$\delta = 2$,$\in = 0.9$,Gr=45)

Biot number	Mass flux	mean temperature
$B_{i_1} = 1$ $B_{i_2} = 1$	0.49394748	0.00541805
$B_{i_1} = 2$ $B_{i_2} = 2$	0.59175097	0.00809413
$B_{i_1} = 3$ $B_{i_2} = 3$	0.66229915	0.00978864

Table12 and Table13 illustrates the effect of varying the Biot number of the plates on the skin-friction, mass flux and Mean temperature respectively, it was observed from the table that increase in the Biot number of the plates lead to increase in the skin-friction on the heated and cold plate, as well as increasing the mass flux and the Mean temperature in the flow domain. This is physically through because increase in the Biot number of the plates lead to increase in the velocity and temperature of the fluid and hence increasing the skin-friction on the heated and cold plate, mass flux and Mean temperature of the fluid in the flow domain.

4. CONCLUSION

This paper has considered a g-jitter effect on transient natural convection Couette flow in a vertical channel with convective boundary condition. The motion is induced by the impulsive motion of one of the channel plates along with by the asymmetric heating of the plates. The influence of the governing parameters on the temperature, velocity, rate of heat transfer, Nusselt number, skin-friction, mass flux and Mean temperature are discussed with the aid of graphs and numerical values. The study concluded that heat generation increase causes an increase in the mass flux and Mean temperature with decreasing thermal diffusivity while heat absorption acts in the reverse. Influence of oscillating frequency of g-jitter on the skin friction depends on time, as an increase in the oscillating frequency of the g-jitter causes the skin friction to increase on the heated plate when time is small. Increase in convective coefficients of the bounding plates constitute an enhancement to heat transfer, skin-friction, mass flux as well as Mean temperature within the channel. Finally the effect of g-jitter on transient natural convection is so significant and as such, it should not be ignored in future studies.

5. NOMENCLATURE

c_p - Specific heat of the fluid at constant pressure

g - Acceleration due to gravity $[ms^{-2}]$

H - Gap between the plates

Pr - Prandtl number

u' - Dimensional fluid velocity $[ms^{-1}]$

u - Dimensionless fluid velocity

$\overleftrightarrow{u}$ –Dimensionless fluid velocity in Laplace domain

U - Velocity of the plate at $y' = h$ for $t' > 0$ $[ms^{-1}]$

t - Dimensionless time

t' - Dimensional time $[s]$

Gr - Grashof number

T_0 - Initial temperature of the fluid and plates at $y' = h$ $[k]$

T_w - The temperature of the plate at $y' = 0$ $[k]$

T' - Dimensional temperature of the fluid $[k]$

y' - Dimensional coordinate perpendicular to the plate $[m]$

x' - Dimensional coordinate parallel to the plate $[m]$

y - Dimensionless coordinate perpendicular to the plate

g^* - Fluctuating acceleration due to gravity (g-jitter) $[ms^{-2}]$

h - Width of the channel $[m]$

Greek alphabets

β - Coefficient of thermal expansion $[k^{-1}]$

κ - Thermal conductivity

μ - Coefficient of viscosity

ν - Kinematic viscosity $[m^2 s^{-1}]$

δ - The heat generating/absorbing

ω - oscillating frequency

ϵ – Amplitude

θ- Dimensionless temperature of fluid

$\overleftrightarrow{\theta}$- Dimensionless temperature of fluid in Laplace domain

6. APPENDIX

The constant used to define temperature, velocity, Nusselt number, skin-friction and Mean temperature

$$\boldsymbol{C_6} = \frac{B_{i_1}(m\boldsymbol{e^m} + B_{i_2}\boldsymbol{e^m})}{\boldsymbol{s}\left(B_{i_2}\boldsymbol{e^{-m}} - \boldsymbol{me^{-m}}\right)\left(\boldsymbol{m} - B_{i_1}\right) + (m\boldsymbol{e^m} + B_{i_2}\boldsymbol{e^m})(m + B_{i_1})}$$

$$\boldsymbol{C_5} = \frac{-\boldsymbol{C_6}\left(B_{i_2}\boldsymbol{e^{-m}} - \boldsymbol{me^{-m}}\right)}{(m\boldsymbol{e^m} + B_{i_2}\boldsymbol{e^m})}$$

$$\boldsymbol{m} = \sqrt{\frac{\boldsymbol{s+B}}{\boldsymbol{A}}}$$

$$\boldsymbol{m^p} = \sqrt{\boldsymbol{s}}$$

$$\boldsymbol{m_1} = \sqrt{\frac{\boldsymbol{p+B}}{\boldsymbol{A}}}$$

$$\boldsymbol{m_2} = \sqrt{\frac{\boldsymbol{q+B}}{\boldsymbol{A}}}$$

$$\boldsymbol{p = s - i\omega}$$

$$\boldsymbol{q = s + i\omega}$$

$$\boldsymbol{A} = \frac{\boldsymbol{1}}{\boldsymbol{Pr}}$$

$$\boldsymbol{B} = \frac{\boldsymbol{\delta}}{\boldsymbol{Pr}}$$

$$\boldsymbol{\bar{u}_{p02} = a_{01} + a_{11} + a_{21} + a_{31} + a_{41} + a_{51}}$$

$$\boldsymbol{\bar{u}_{p03} = a_{01}e^{m} + a_{11}e^{-m} + a_{21}e^{m_1} + a_{31e^{-m_1}} + a_{41}e^{m_2} + a_{51}e^{-m_2}}$$

$$\boldsymbol{C_{41}} = \frac{\boldsymbol{1}}{\boldsymbol{s(1 - e^{-2m^p})}} + \frac{\boldsymbol{\bar{u}_{p03}e^{-m^p}}}{\boldsymbol{(1 - e^{-2m^p})}} - \frac{\boldsymbol{\bar{u}_{p02}}}{\boldsymbol{(1 - e^{-2m^p})}}$$

$$\boldsymbol{C_{31} = -C_4e^{-2m^p} - \bar{u}_{p03}e^{-m^p}}$$

$$\boldsymbol{a_{01}} = \frac{\boldsymbol{-GrC_5}}{\boldsymbol{m^2 - s}}$$

$$\boldsymbol{a_{11}} = \frac{\boldsymbol{-GrC_6}}{\boldsymbol{m^2 - s}}$$

$$\boldsymbol{a_{21}} = \frac{\boldsymbol{-GrC_5\epsilon}}{\boldsymbol{2i(m_1^2 - s)}}$$

$$\boldsymbol{a_{31}} = \frac{\boldsymbol{-GrC_6\epsilon}}{\boldsymbol{2i(m_1^2 - s)}}$$

$$\boldsymbol{a_{41}} = \frac{\boldsymbol{GrC_5\epsilon}}{\boldsymbol{2i(m_2^2 - s)}}$$

$$\boldsymbol{a_{51}} = \frac{\boldsymbol{GrC_6\epsilon}}{\boldsymbol{2i(m_2^2 - s)}}$$

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