Journal of the Nigerian Association of Mathematical Physics
Volume **15 (November, 2009), pp 469- 476**

Entropy generation in MHD flow of a uniformly stretched vertical permeable surface under oscillatory suction velocity

[1]A. M. Okedoye and A. O. Adesanya
Department of Pure and Applied Mathematics,
Ladoke Akintola University of Technology,
P. M. B.* 4000. *Ogbomoso, Nigeria

Abstract

This paper reports the analytical calculation of the entropy generation due to heat and mass transfer and fluid friction in steady state of a uniformly stretched vertical permeable surface with heat and mass diffusive walls, by solving analytically the mass, momentum, species concentration and energy balance equation, using asymptotic method. The velocity, temperature and concentration profiles were reported and discussed. The influences of the chemical reaction parameter, the thermal and mass Grashof numbers, heat generation/absorption and Hartmann number on total entropy generation were investigated, reported and discussed.

Keywords
Heat transfer, Mass transfer, Entropy generation, Fluid friction, MHD flow, suction velocity, viscousity

AMS Subject Classification: 76W05

Nomenclature

c : non-dimensional concentration
T : fluid temperature
u: fluid axial velocity
C_j : skin-friction coefficient
Grc : mass Grasho number
$Gr\tau$: thermal Grashof number
M :Hartmann number
Nu : Nuselt number
Sh : Sherwood number
Pr : Prandtl number
v : fluid transverse velocity
K : non-dimensional reaction parameter
c_p: specific heat at constant pressure
y : transverse or horizontal coordinate
k_0 = *K0*: permeability parameter
t : time
$i = \sqrt{-1}$: complex identity

Greek Symbols

θ: non - dimensional fluid temperature
ϕ : heat generation/absorption coefficient
ω : angular velocity

Dimensionless Group

Grt : dimensionless thermal Grashof number
Grc : dimensionless mass Grashof number
ε: epsilon, $0 \leq \varepsilon << 1$

Subscripts

ω : condition on the wall
∞: ambient condition

[1]Corresponding author
[1]e–mail address: micindex@yahoo.com,
[1]Telephone: +234-0803–568-8 453

1.0 Introduction

In industries and nature, many transport processes exist in which heat and mass transfer takes place simultaneously as a result of combined buoyancy effect of thermal diffusion and diffusion of chemical species. The phenomenon of heat and mass transfer is observed on buoyancy induced motions in the atmosphere, in bodies of water, quasi – solid bodies, such as earth and so on. Unsteady oscillatory free convective flows play an important role in chemical engineering, turbo machinery and aerospace technology such flows arise due to either unsteady motion of a boundary or boundary temperature. Besides unsteadiness may also be due to oscillatory free stream velocity and temperature. In the past decades an intensive research effort has been devoted to problems on heat and mass transfer in view of their application to astrophysics, geophysics and engineering. In addition, the phenomenon of heat and mass transfer is also encountered in chemical process industries such as polymer production and food processing. The study of flow and, heat and mass transfer in the boundary layer induced by a surface moving with a uniform or non-uniform velocity in a quiescent ambient fluid is important in several manufacturing processes in industry which include the boundary layer along material handling conveyors, the cooling of an infinite metallic plate in a cooling bath, Glass blowing, continuous casting, and spinning of fibers also involve the flow due to a stretching surface.

Many researchers [1-10] have studied the problem on free convection and mass transfer flow of a viscous fluid through porous medium. In these studies, the permeability of the porous medium is assumed to be constant. However, a porous material containing the fluid is a non – homogeneous medium and the porosity of the medium may not necessarily be constant. Recently, [11] have discussed analytical solutions for unsteady free convection in porous media. MHD flow of a uniformly stretched vertical permeable surface under oscillatory suction velocity was reported by [12]. In their paper, the suction velocity is assumed to be $\left(1+B\in e^{iwt}\right)$ and the permeability is taken to be $\dfrac{1}{k(1+\in e^{i\omega t})}$.

In the traditional approach in numerical computation of double diffusive convection problems, the quantities to be computed are usually temperature, pressure, concentration, mass and heat flow rates, but infrequently involving entropy properties. The contemporary trend in the field of heat transfer and thermal designs is the second Law (of Thermodynamics) analysis and its design-related concept of entropy generation minimization [13]. Entropy generation is associated with thermodynamic irreversibility, which is common in all types of heat transfer processes. Different sources of irreversibility are responsible for heat transfer's generation of entropy like heat transfer across finite temperature gradient, viscous effects, characteristics of convective heat transfer, etc. Thus entropy generation depends functionally on the local values of velocity and temperature in the domain of interest. Energy conversion processes are accompanied by an irreversible increase in entropy, which leads to a decrease in available energy.

For a given system, a set of thermodynamic parameters, which optimize the operating conditions, may be obtained. Nag and Kumar [14] studied second Law optimization for convective heat transfer through a duct with constant heat flux. In their study, they plotted the variation of entropy generation versus the temperature difference of the bulk and the surface flow, using a dusty parameter. Shuja and Yilbas [15] analyzed the entropy generation in an impinging jet and Shuja and co–workers [16, 17, 18] consider swirling jet impingement on an adiabatic wall for various flow conditions. The dissipation of energy takes the form of a sum of products of conjugate forces and fluxes associated to the problem under consideration; this was presented by the text of [19]. The fluxes are expressed as linear functions of all forces, as constitutive equations, subjected to the reciprocal relations of Onsager. These lead to coupled field equations for the temperature and species concentrations in a given fluid mixture. Interferences between heat and mass transport, at the level of constitutive equations, and the linear theory of non-equilibrium thermodynamics had been formulated as a constitutive theory capable of fully expressing the dependence of all fluxes as a function of all thermodynamic forces. Entropy generation in MagnetoHydroDynamic (MHD) flow of uniformly stretched vertical permeable surface in the presence of heat generation/absorption and chemical reaction was studied and reported by [21]

Although the various topics investigated about entropy generation and its minimization, the determination of total irreversibility in MHD flow under oscillatory suction velocity has not been encountered. In this context, the present paper reports an analytical determination of the entropy generation in Magneto – Hydro - Dynamic (MHD) flow of a uniformly stretched vertical permeable surface under oscillatory suction velocity

2.0 Mathematical formulation

An unsteady magnetohydrodynamic flow of viscous, incompressible, electrically conducting fluid past an infinite plate in a porous medium of time dependent permeability and suction velocity is considered. In Cartesian co – ordinate system, *x*-axis is assumed to be along the plate in the direction of the flow and *y*–axis normal to it. A uniform magnetic field is introduced normal to the direction of the flow. In the analysis, it is assumed that the magnetic Reynold number is much less than unity so that the induced magnetic field is neglected in comparison to the applied magnetic field. Further, all the fluid properties are assumed to be constant except that of the influence of density variation with temperature. Therefore, the basic flow in the medium is entirely due to buoyancy force caused by temperature difference between the wall and the medium. Initially at $t = 0$, the plate as well as fluid is assumed to be at the same temperature and concentration of species is very low so that the Soret and Dofour effect are neglected [12]. When $t = 0$, the temperature of the plate is instantaneously raised (or lowered) to T_w and the concentration of the species raised (or lowered) to c_w. Under the stated assumptions and taking the usual Buossinesqs approximation in to account, the non dimensional governing equations for momentum, energy and concentration are:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \left(1 + \in e^{i\omega t}\right)\frac{\partial u}{\partial y} = Gr\,\tau\theta + Gr \cdot c + \frac{\partial u^2}{\partial y^2} - \left(\frac{1}{k(1 + \in e^{i\omega t})} + M^2\right)u \qquad (2.1)$$

$$\frac{1}{4}\frac{\partial \theta}{\partial \tau} - \left(1 + \in e^{i\omega t}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} + \phi\theta \qquad (2.2)$$

$$\frac{1}{4}\frac{\partial c}{\partial \tau} - \left(1 + \in e^{i\omega t}\right)\frac{\partial c}{\partial y} = \frac{1}{Sc}\frac{\partial^2 c}{\partial y^2} - Kc \qquad (2.3)$$

where the parametersn ε, ω, *Grτ, Grc, k, Pr, Sc, M,* ϕ and *K* were as defined in nomenclature.

The corresponding boundary conditions are

$$\begin{aligned} &u = 0, \theta = 1 + \in e^{i\omega t}, c = 1 + \in e^{i\omega t} \, as \; y = 0 \\ &u \to 0, \theta \to 0, c \to o \, as \; y \to \infty \end{aligned} \qquad (2.4)$$

3.0 Method of solution

We seek an asymptotic expansion about $\in$ for our dependent variables of the form:

$$\left.\begin{aligned} u(y,t) &= u_o(y) + \in u_1 e^{i\omega t} + o(\in^2) + \ldots \\ \theta(y,t) &= \theta_o(y) + \in \theta_1 e^{i\omega t} + o(\in^2) + \ldots \\ c(y,t) &= c_o(y) + \in \theta_1 e^{i\omega t} + o(\in^2) + \ldots \end{aligned}\right\} \tag{3.1}$$

Substituting (3.1) into equations (2.1) – (2.4) and collecting the terms in power of ε, we have the following sets of equations; corresponding to the energy equation we have,

$$\frac{d^2\theta_o}{dy^2} + \Pr\frac{d\theta_o}{dy} + \Pr\theta_o = 0 \tag{3.2}$$

$$\theta_o(0) = 1, \theta_o(y) \to 0 \; as \; y \to \infty$$

$$\frac{d^2\theta_1}{dy^2} + \Pr\frac{d\theta_1}{dy} + \Pr\left(\frac{i\omega}{4} + \phi\right)\theta_1 = -\frac{d^2\theta_o}{dy}$$

$$\theta_1(y) = e^{i\omega t} as \; y = 0 \tag{3.3}$$

$$\theta_1(y) \to 0 \; as \; y \to \infty$$

Corresponding to the specie equation we have,

$$\frac{d^2c_0}{dy^2} + Sc\frac{dc_0}{dy^2} - KScc_0 = 0 \tag{3.4}$$

$$c_0(0) = 1, c_0(y) \to 0 \; as \; y \to \infty$$

$$\frac{d^2c_1}{dy^2} + Sc\frac{dc_1}{dy} + Sc\left(\frac{i\omega}{4} - K\right)c_1 = -\frac{dc_0}{dy} \tag{3.5}$$

$$c_1(y) = e^{i\omega t} \; at \; y = 0, \; c_1(y) \to 0 \; as \; y \to \infty$$

And corresponding to the momentum equation we have,

$$\frac{d^2u_0}{dy^2} + \frac{du_0}{dy} - \left(\frac{1}{k_0} + M^2\right)u_0 = -Gr\tau\theta_0 - Grcc_0 \tag{3.6}$$

$$u_o(0) = 0, u_0(\infty) = 0$$

$$\frac{d^2u_1}{dy^2} + \frac{du_1}{dy} - \left(\frac{1}{k_0} + M^2\right)u_1 = \frac{i\omega}{4}u_1 - Gr\tau\theta_1 - Gtcc_1 - \frac{1}{k_0}u_0$$

This is simplified as

$$\frac{d^2u_1}{dy_2} + \frac{du_1}{dy} - \left(\frac{1}{k_0} + \frac{i\omega}{4} + M^2\right)u_1 = -Gr\tau\theta_1 - Grcc_1 - \frac{1}{k_0}u_0 - \frac{du_0}{dy} \tag{3.7}$$

$$u_1(0) = 0, u_1(\infty) = 0$$

Using method of undetermined coefficients [12] the solutions to the asymptotic equations (2.1) to (3.7) are:

$$\theta_0(y) = e^{-my}, \tag{3.8}$$

$$\theta_1(y) = a_1 e^{-my} + a_2 e^{-m_1 y} \tag{3.9}$$

$$c_0(y) = e^{-ny}, \; n = \frac{1}{2}\left(Sc + \sqrt{Sc^2 + 4KSc}\right), \tag{3.10}$$

$$c_1(y) = a_3 e^{-ny} + a_4 e^{-n_1 y}, \tag{3.11}$$

$$u_0(y) = a_5 e^{-my} + a_6 e^{-ny} + a_7 e^{-ry} \tag{3.12}$$

$$u_1(y) = a_8 e^{-my} + a_9 e^{-m_1 y} + a_{10} e^{-ny} + a_{11} e^{-ny} + a_{12} e^{-ry} + a_{13} e^{-r_1 y} \tag{3.13}$$

where $m = \frac{1}{2}\left(\Pr + \sqrt{\Pr^2 - 4\Pr\phi}\right)$, $n_1 = \frac{1}{2}\left(Sc + \sqrt{Sc^2 + 4Sc\left(-K + \frac{iw}{4}\right)}\right)$,

$$r = \frac{1}{2}\left(1 + \sqrt{1 + 4\left(\frac{1 + k_0 M^2}{k_0}\right)}\right), \; a_1 = -\frac{4mi}{\Pr\omega}, \; a_2 = e^{i\omega t} - a_1, \; a_3 = -\frac{4ni}{Sc\omega} \;\; a_4 = e^{iwt} - a_3,$$

$$a_5 = \frac{-Gr\tau}{m^2 - m - (\frac{1}{k_0} + M^2)}, \; a_6 = \frac{-Grc}{n^2 - n - \left(\frac{1}{k_0} + M^2\right)}, \; a_8 = -\frac{\left(a_1 Gr\tau + a_5\left(\frac{1}{k_0} - m\right)\right)}{m^2 + m(\frac{1}{k_0} + m^2 + \frac{i\omega}{4})},$$

$$a_9 = \frac{-a_2 Gr\tau}{m^2{}_1 - m_1 - \left(\frac{1}{k_0} + M^2 + \frac{i\omega}{4}\right)}, \; a_{10} = -\frac{\left(Grca_3 + a_6\left(\frac{1}{k_0} - n\right)\right)}{n^2 - n - \left(\frac{1}{k_0} - M^2 + \frac{i\omega}{4}\right)},$$

$$a_{11} = \frac{-a_4 Grc}{n^2{}_1 + n_1 - \left(\frac{1}{k_0} + M^2 + \frac{i\omega}{4}\right)}, \; a_{12} = \frac{-4ia_7(1 - rk_o)}{\omega k_o}, \; a_{13} = -(a_8 + a_9 + \ldots.. + a_{12})$$

4.0 Entropy generation rate

For an incompressible Newtonian fluid, the local entropy generation rate is given by [20]:

$$\Gamma = \frac{\mu}{T}\left(\frac{\partial u_i}{\partial x_j}\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{1}{T}\sum_\alpha J\alpha_i\left(\frac{\partial u_\alpha}{\partial x_i}\right) - \frac{q}{T^2}\left(\frac{\partial T}{\partial x_i}\right) - \frac{1}{T}\sum_\alpha S_\alpha J\alpha_i\left(\frac{\partial u_\alpha}{\partial x_i}\right) - \frac{1}{T}\sum_\alpha K_\alpha \mu_\alpha$$

On the right hand side of the above equation, the first term is due to fluid friction, the second is due to mass diffusion and the third term is due to heat conduction. The fourth term is due to heat transfer induced by mass diffusion and the fifth is due to chemical reactions. In the case of non – reactive mixture, the heat due to diffusion is negligible, and thus the entropy generation rate is rewritten as

$$\Gamma = \frac{\mu}{T}\left(\frac{\partial u_i}{\partial x_j}\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{1}{T}\sum_\alpha J\alpha_i\left(\frac{\partial u_\alpha}{\partial x_i}\right) - \frac{q}{T^2}\left(\frac{\partial T}{\partial x_i}\right)$$

In convective heat and mass transfer and MHD flow, irreversibility arises due to the heat transfer, the viscous effects and the mass transfer. The entropy generation rate is expressed as the sum of contributions due to viscous, thermal and diffusive effects, and thus it depends functionally on the local values of temperature, velocity and concentration in the domain of interest.

According to [13], the characteristic entropy transfer rate is given by:

$$\Gamma_0 = k\left(\frac{\Delta T}{LT_0}\right) \tag{4.1}$$

Where k, L, T_o and ΔT are respectively, the thermal conductivity, the characteristic length of the enclosure, a reference temperature and a reference temperature difference.

Okedoye et al [21] defined the two –dimensionless entropy Generation rate as

$$\Gamma_n = \left(\frac{\partial\theta}{\partial y}\right)^2 + \lambda_1\left(\frac{\partial u}{\partial y}\right)^2 + \lambda_2\left(\frac{\partial c}{\partial y}\right)^2 + \lambda_3\left(\frac{\partial\theta}{\partial y}\right)\left(\frac{\partial c}{\partial y}\right) \tag{4.2}$$

We can now define the followings:

$$\Gamma_{n,h} = \left(\frac{\partial\theta}{\partial y}\right)^2,\ \Gamma_{n,f} = \lambda_1\left(\frac{\partial u}{\partial y}\right)^2,\ \Gamma_{n,d}^{c} = \lambda_2\left(\frac{\partial c}{\partial y}\right)^2, \text{ and } \Gamma_{n,d}^{c,T} = \lambda_3\left(\frac{\partial\theta}{\partial y}\right)\left(\frac{\partial c}{\partial y}\right),$$

where $\Gamma_{n,h}$ and $\Gamma_{n,f}$ are thermal and viscous irreversibility respectively, while $\Gamma_{n,d}^{c} + \Gamma_{n,d}^{c,T}$ is the diffusive irreversibility. Dimensionless terms denoted λ_i($1 \le i \le 3$, and called irreversibilities distribution ratios, are given by:

$$\lambda_1 = \frac{\mu T_0}{k}\left(\frac{a}{L(\Delta T)}\right)^2,\quad \lambda_2 = \frac{RDT_0}{kc_0}\left(\frac{\Delta c}{\Delta T}\right)^2,\quad \lambda_3 = \frac{RD}{k}\left(\frac{\Delta c}{\Delta T}\right) \tag{4.3}$$

Where C_o and T_o are respectively the reference concentration and temperature, which are in our case, the bulk concentration and the bulk temperature.

The local entropy generation rate is a function of temperature and velocity gradients in the y directions in the entire calculation domain.

Using the above equation, on substituting equations (3.8) to (3.13) for irreversibilities, we have

$$\begin{aligned}\Gamma = &\left(-me^{-my} + \varepsilon e^{i\omega t}\left(-a_1 me^{-my} - a_2 m_1 e^{-m_1 y}\right)\right)^2 + \lambda_1\left(-a_5 me^{-my} - a_6 ne^{-ny} - a_7 re^{-ry} + \right.\\ &\left.\varepsilon e^{i\omega t}\left(-a_8 me^{-my} - a_9 m_1 e^{-m_1 y} - a_{10} ne^{-ny} - a_{11} n_1 e^{-n_1 y} - a_{12} re^{-ry} - a_{13} r_1 e^{-r_1 y}\right)\right)^2\\ &\lambda_2\left(-ne^{-ny} + \varepsilon e^{i\omega t}\left(-a_3 me^{-my} - a_4 n_1 e^{-n_1 y}\right)\right)^2 + \lambda_3\left(-a_5 me^{-my} - a_6 ne^{-ny} - a_7 re^{-ry} + \right.\\ &\left.\varepsilon e^{i\omega t}\left(-a_8 me^{-my} - a_9 m_1 e^{-m_1 y} - a_{10} ne^{-ny} - a_{11} n_1 e^{-n_1 y} - a_{12} re^{-ry} - a_{13} r_1 e^{-r_1 y}\right)\right)\left(-me^{-my} + \right.\\ &\left.\varepsilon e^{i\omega t}\left(-a_1 me^{-my} - a_2 m_1 e^{-m_1 y}\right)\right)\end{aligned} \tag{4.4}$$

5.0 Discussion

In this study, four dimensionless numbers (ω, $Gr\tau$, Grc, k, Pr, Sc, M, ϕ and K) are used in the governing combined heat and mass transfer equations. The exploitation of the entropy generation equation limits the choices of the Prandtl and the Schmidt numbers to the case of plasma only. Furthermore the Prandtl and Schmidt numbers are fixed at 0.71 and 0.6 respectively.

The analytical simulations presented in this work has been conducted in order to study the effects of the thermal and mass Grashof numbers, heat generation/absorption, chemical reaction parameter, permeability factor and the Hartmann number on entropy generated in steady state conditions.

For small thermal Grashof number, there is practically little or no convection and the entropy generation due to fluid friction is zero, consequently the total entropy generation is reduced to the entropy generation due to heat transfer. At higher Grashof number heat transfer due to convection begins to play a significant role increasing the flow velocity and in turn the entropy generation due to the viscous effects. Also the isotherms are deformed, which increases the temperature gradient and consequently the entropy generation due to heat transfer. For our analysis, the values assigned to the constants are: K_0 = 0.31, *Sc* = 0.6, *Pr* = 0,71, *t* = 1, *Grt* = 1, ε = 0.2, *Grc* = 1, ϕ = 1.5, *M* = 0.5, *K* = -1. $\omega = 1.571, \lambda_1 = 0.8, \lambda_2 = 0.4$ and $\lambda_2 = 0.4$ unless where stated otherwise. The entropy generated is highest at the surface and continually decreases to zero far from the plate. The entropy generated increases as generative chemical reaction increase and decrease as destructive chemical reaction increase; this is shown in figure

5.1. The effect of permeability parameter on the entropy is shown in figure 5.2, it could be seen that increase in permeability leads to increase in entropy generated. Entropy generated has maximum values when the magnetic induction is zero and decrease for values either side of 0, as shown in figure 5.3 it could be seen that entropy generated decrease faster close to the plate. We displayed in figure 5.4 the effect of ϕ on entropy, it is observed that increase in heat absorption leads to increase in entropy generated. Figures 5.5 and 5.6 shows the effect of mass and thermal grashof numbers respectively on the entropy generated. It could be seen that increase in either mass or thermal grashof number resulted into increase in entropy. The oscillatory effect of ω on the entropy is shown in figure 5.7. At any point during the flow, the entropy generated oscillate as position element or ω increases.

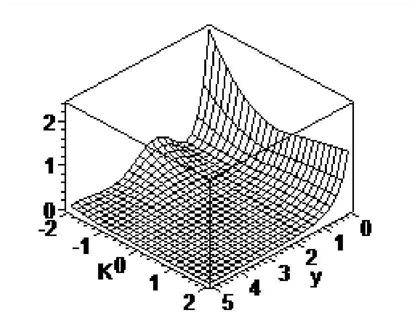

Figure 5.1: Entropy distribution as a function of reaction parameter (y, K)

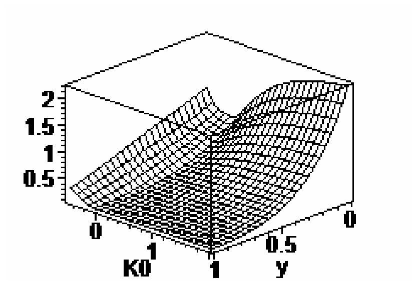

Figure 5.2: Entropy distribution for various values of permeability factor

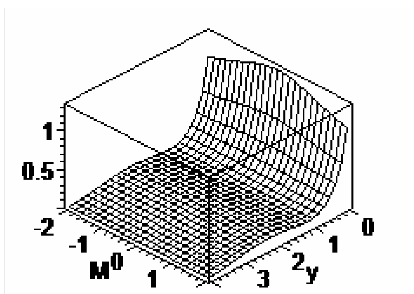

Figure 5.3: Entropy distribution for various values of magnetic induction

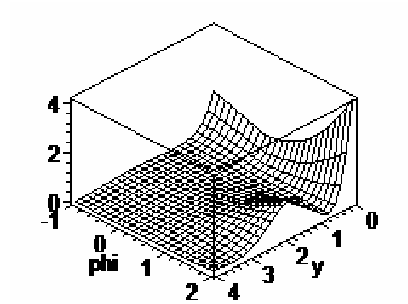

Figure 5.4: Entropy distribution for various values of heat

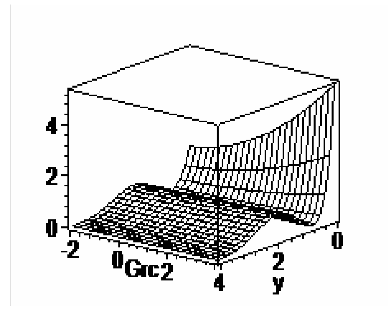

Figure 5.5: Entropy distribution for various values of mass grashof number generation/absorption

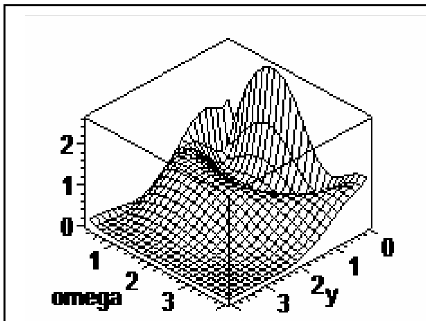

Figure 5.7: Entropy distribution as function of ω

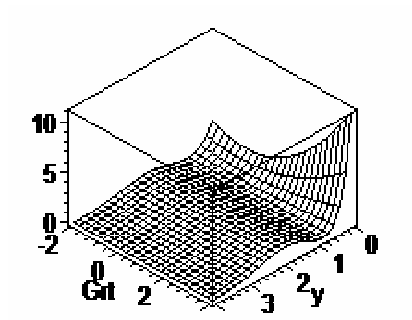

Figure 5.6: Entropy distribution for various values of thermal grashof number generation/absorption

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