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ON ENTROPY IN BUOYANT MHD RADIATIVE FLOW PAST A VERTICAL PLATE EMBEDDED IN POROUS MEDIUM

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Abstract: The paper presents entropy generation analysis for the radiative MHD buoyant boundary-layer flow past a vertical plate embedded in a fluid saturated porous medium. The plate bears a uniform temperature T_w and the uniform temperature of the fluid far away from the plate is $T_{\infty.}$ A Cartesian coordinate system is chosen where the x-axis is taken along the vertical plate directed upwards and the y-axis is taken perpendicular to the plate. A uniform magnetic field B is applied normal to the plate. The flow is primarily caused by the density variation impressed upon by the temperature difference. A similarity transformation followed by Runge-Kutta scheme together with shooting method is employed to solve the governing equations. Numerical calculations of quantities of interest conducted for various sets of parameters values are portrayed graphically, in tabular form and discussed.

Keywords: Entropy, buoyancy, viscous dissipation, radiation.

1. Introduction

Studies in heat transfer in presence of porous media were prompted due to wide array of industrial and technological applications. In fact, convection in porous media got prominence as a research domain simply because many mechanical, chemical and civil engineering systems involve thermally driven flow in porous media. These include fibrous insulation, food processing and storage, thermal insulation of buildings, geophysical systems, metallurgy, pebble bedded nuclear reactors, management of nuclear /non-nuclear waste, electronic cooling, etc. Flow configuration involving heated surface bounding a clear fluid and /or fluid saturated porous medium has been much investigated owing to ample applications in existing systems or for devising systems of interest. As far as porous medium configurations involving vertical plate is concerned, these were treated for Darcian and non Darcian regimes involving Brinkman and other models considering effective viscosity of porous medium, porosity, form drag etc. The literature is abundant on the configuration covering wide range of issues. Ostrach [23] conducted an analysis of laminar free convection flow and heat transfer about a flat plate. Cess [7] reported the interaction of thermal radiation with free convection heat transfer. Hasegawa et al. [12] reported analytic and experimental studies on simultaneous radiative and free convective heat transfer along a vertical plate. Pera and Gebhart [25] considered natural convection boundary layer over horizontal and slightly inclined surfaces. Kao [17] investigated laminar free convective heat transfer along a vertical flat plate with step jump in surface temperature. Messiter and Liñán [21] examined leading and trailing edges and discontinuous temperature effects on laminar free convection due to a vertical plate. Cheng and Minkowycz [9] considered heat transfer from a vertical flat plate placed in a porous medium. Evans and Plumb [10] studied natural convection from a vertical isothermal surface embedded in a saturated porous medium. Soundalgekar and Ganesan [29] conducted finite difference analysis of transient free convection with mass transfer on an isothermal vertical flat plate. Raptis and Kafousias [27] studied MHD heat transfer in flow through a porous medium bounded by an infinite vertical plate. Hong et al. [14] examined non-Darcy effect on vertical plate natural convection in porous media with high porosity. Takhar et al. [31] presented an analysis of radiation effect on MHD free convection flow of a radiating gas past a semi-infinite vertical plate. Helmy [13] investigated MHD unsteady free convection flow past a vertical porous plate. Lensic et al. [19] reported free convection adjacent to vertical surface subjected to Newtonian heating in a porous medium. Israel-Cookey [15] investigated Influence of viscous dissipation and radiation on unsteady MHD free-convection flow past an infinite heated vertical plate in a porous medium with time-dependent suction. Postelnicu [26] reported influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects. Pantokratoras [24] analysed effect of viscous dissipation in natural convection along a heated vertical plate. Abo-Eldahab and Aziz [2] considered a rather complex setup to study viscous dissipation and Joule heating effects on MHD-free convection from a vertical plate with power-law variation in surface temperature in the presence of Hall and ion-slip currents. Magyari and Rees [20] studied effect of viscous dissipation on the Darcy free convection over a vertical plate with exponential temperature distribution in a porous medium. Alam et al. [3] studied Dufour and Soret Effects on Unsteady MHD Free Convection and Mass Transfer Flow past a Vertical Porous Plate in a Porous Medium. Kuznetsov and Nield [18] extended the discussion taking natural convective boundary-layer flow of a nano-fluid past a vertical plate. Singh [28] investigated mixed convection boundary layer flow past a vertical plate in porous medium with viscous dissipation and variable permeability. Abdullahi [1] examined heat and mass transfer with radiation and dissipation over a fixed vertical plate. Srinivasacharya and Ontela [30] examined non-similar solution for natural convective boundary layer flow of a nanofluid past a vertical plate embedded in a doubly stratified porous medium. Ferdows and Liu [11] considered natural convective flow of a magneto-micropolar fluid along a vertical plate.

This research paper presents an insight about thermodynamic irreversibility in a buoyant Darcian regime wherein the fluid saturated porous medium is bounded by a vertical plate. The flow model is solved numerically and highlights the dissipative and buoyant effects on the hydrodynamic and thermal quantities of interest. The findings have been presented through tables and graphs.

Thermodynamic irreversibility in fluidics has received attention for devising energy efficient systems. It has been realised that parametric study of entropy generation is much insight giving for entropy generation minimization. Many authors have reported pertinent investigations on entropy generation in variety of flow configurations [8, 32 -37]

2. Mathematical Model

Let us consider a boundary- layer flow over a vertical impermeable plate embedded in a fluid saturated porous medium. We consider the x-axis along the vertical plate directed upwards and y-axis perpendicular to the plate. The plate bears a uniform temperature T_w and the temperature of the fluid far away from the plate is T_∞. A uniform magnetic field B is applied as shown in the schematic diagram (Fig.1). The flow is caused by the density variation impressed upon by the temperature difference. Employing boundary layer approximations in Darcy flow regime, the governing partial differential equations [16, 22] are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$u = \frac{K}{\nu} g\beta_T (T - T_\infty) - \frac{K\sigma B^2}{\nu\rho \in} u \tag{2}$$

$$\rho C_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \kappa \frac{\partial^2 T}{\partial y^2} + \mu\left(\frac{\partial u}{\partial y}\right)^2 - \frac{\partial q_r}{\partial y} \tag{3}$$

The boundary conditions at the plate are given by

$$y = 0: \quad u = 0,\ v = 0,\ T = T_W \tag{4}$$

$$y \to \infty: \quad u = 0, \quad T \to T_\infty \tag{5}$$

Where (u, v) are the velocities in (x, y) directions respectively, ν is the kinematic velocity, β_T is the thermal coefficient, κ is the thermal conductivity, K is the permeability of the porous medium, σ is the electric conductivity, B is the applied magnetic field, ρ is the fluid density, $\in$ is the porosity, C_p is the specific heat at constant pressure.

Rooseland approximation [6] allows radiative flux q_r to be written as follows

$$q_r = -\frac{4\beta}{3\gamma}\frac{\partial T^4}{\partial y} \tag{6}$$

where β and γ are the Stephen-Boltzmann constant and the mean absorption coefficient respectively. It is assumed that the temperature difference within the flow is small enough to express T^4 as a linear function of temperature T about the free stream temperature T_∞. A truncated Taylor series of T about T_∞ yields

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

We introduce the following similarity transformations and dimensionless parameters

$$\eta = \frac{y(Ra)^{1/2}}{x},\ \theta = \frac{T - T_\infty}{T_w - T_\infty},\ u = \frac{Ra\alpha}{x} f',\quad v = \frac{\alpha(Ra)^{1/2}}{2x}(f - \eta f') \tag{8}$$

Where

$Ra = \dfrac{K\beta_T x g(T_w - T_\infty)}{\nu\alpha}$ is the local Rayleigh number and $\alpha = \dfrac{\kappa}{\rho C_p}$ is the thermal diffusivity.

On using Eq. (6) through Eq. (8), the Eq. (2) and Eq. (3) reduce to

$$(1 + M^2)\, f'(\eta) = \theta(\eta) \tag{9}$$

$$-\frac{f(\eta)\,\theta'(\eta)}{2} = (1+N)\,\theta''(\eta) + Ec\,(f''(\eta))^2 \tag{10}$$

and the boundary conditions (4) and (5) become

$$\eta = 0: \qquad \theta = 1,\quad f = 0 \tag{11}$$

$$\eta \to \infty: \qquad \theta = 0,\quad f' = 0 \tag{12}$$

where $M^2 = Ra\dfrac{\sigma\alpha B^2}{x\rho \in g\beta(T_w - T_\infty)}$ is the magnetic field parameter, $Ec = \dfrac{g^2\beta_T^2K^2\mu}{\nu^2 k}(T_w - T_\infty)$ is the modified Eckert number and $N = \dfrac{16\beta T_\infty^3}{3\delta\kappa}$ is the radiation parameter.

3. Solution Method

The governing BVP given by Eq. (9) through Eq. (12) has been solved numerically by fourth order Runge-Kutta scheme together with shooting method. In order to employ shooting method we reduce the BVP into a system of initial value problems. These conversions give rise to unknown quantities which have to be estimated. In this case, the reduction of the BVP into a system of initial value problem goes as follows :

$$\frac{\partial f}{\partial \eta} = p \tag{13}$$

$$\frac{\partial\theta}{\partial\eta} = q \tag{14}$$

$$p = \frac{\theta(\eta)}{(1+M^2)} \tag{15}$$

$$\frac{\partial q}{\partial\eta} = -\frac{1}{(1+N)}\left\{Ec\left(\frac{\partial p}{\partial\eta}\right)^2 + \frac{fq}{2}\right\} \tag{16}$$

Together with the initial conditions

$$f(0) = 0,\ \theta(0) = 1,\ q(0) = \frac{d\theta}{d\eta}(0) = a_0 = ? \tag{17}$$

We solve the above system of IVP's with the appropriate guess value for the unknown quantity $\theta'(0) = a_0$ so that the conditions at the end $\theta(\infty) = 0$ and $f'(\infty) = 0$ are satisfied. If the boundary conditions are not satisfied with this guess value, then the procedure is again repeated for another guess values until the end conditions are satisfied up to the prescribed accuracy. These guess values were chosen purely on hit and trial basis and refined further by secant method with prescribed error tolerance of order 10^{-6} together with grid space $\Delta\eta = 0.001$.

The computations performed on MATLAB provided numerical values for the velocity and temperature fields.

4. Second Law Analysis

The local volumetric rate of entropy generation S_G for the configuration under study is given as follows [4, 5, 37]

$$S_G = \frac{\kappa}{T_\infty^2}\left\{\left(\frac{\partial T}{\partial y}\right)^2 + \frac{16\beta T_\infty^3}{3\delta\kappa}\left(\frac{\partial T}{\partial y}\right)^2\right\} + \frac{\mu}{T_\infty}\left(\frac{\partial u}{\partial y}\right)^2 \tag{18}$$

We prescribe the characteristic entropy generation rate, the temperature ratio and the entropy generation number respectively as follows:

$$S_{G_0} = \frac{\kappa(T_w - T_\infty)^2 Ra}{T_\infty^2 x^2},\ \omega = \frac{T_\infty}{T_w - T_\infty},\ N_S = \frac{S_G}{S_{G_0}} \tag{19}$$

Thus, entropy generation number N_s is found to be

$$N_S = (1 + N)(1 + M)\left(\frac{d\theta}{d\eta}\right)^2 + Ec\omega\left(\frac{d^2f}{d\eta^2}\right)^2 \tag{20}$$

The global entropy is computed by integrating the entropy generation number N_s across the solution space. Hence, we have

$$G_{Ns} = \int_0^{\eta_\infty} N_s d\eta \tag{21}$$

The integral (21) has been computed numerically by the Simpson's 1/3 rule to yield:

$$G_S = \frac{1}{3}\left[\left(N_{s_0} + N_{s_{n+1}}\right) + 4\left(N_{s_1} + N_{s_3} + \ldots + N_{s_n}\right) + 2\left(N_{s_2} + N_{s_4} + \ldots + N_{s_{n-1}}\right)\right] \tag{22}$$

5. Results and Discussions

The computed results for velocity, temperature and entropy generation number for the parameters involved have been shown graphically. The global entropy has been presented in the Tables 1-4. Figure 2 reveals that there is a rise in velocity with an increase in Eckert number Ec that accounts for dissipative effect. The figure 3 displays velocity profiles for varying values of M. It is found that velocity decays with increasing values of Hartmann number M. The figure 4 shows velocity profiles for varying values of N. It is seen that the velocity increases with increasing values of radiation parameter N. The figure 5 portrays temperature profiles for varying values of Ec. We find that the temperature increases with increasing values of Ec. Figures 6 and 7 respectively reveal that temperature increases with the increasing values of M and N.

The distribution of local entropy has been depicted in the figures 8-11. It is seen that the spatial distribution of entropy for the varying values of the parameters Ec and M is peculiarly different in contrast to the parameters N and ω. To be specific, from the figures 8 and 9 we observe that the N_S decreases in the vicinity of the plate with increasing values of Ec and M. However, the trend is reversed at some spatial distance from the plate i.e. at $\eta = 2$ and $\eta = 4$ respectively. Further, we note that there is a pronounced qualitative generation in entropy adjacent to the wall that continually decays as we move away from it. The figures 10 and 11 respectively show that the N_S increases with the increasing values of N and ω.

The global entropy is a pertinent indicator of inherent thermodynamic irreversibility. It is nothing but sum of the total entropy generated across the flow domain. The Tables 1 - 4 present effects of the parameters on global entropy G_{Ns}. The Table - 1 shows that G_{Ns} decreases with an increase in Hartmann number M. The Table - 2 shows that with an increase in Ec, there is a rise in global entropy. The Table - 3 shows that G_{Ns} rises with an increase in radiation parameter N. The Table - 4 shows that G_{Ns} registers an increase with an increase in characteristic temperature ratio ω.

6. Conclusions

The problem underscores that the buoyancy has a qualitative and quantitative effect on the velocity and temperature fields and consequently has a qualitative and quantitative bearing on entropy distribution. The study reveals that

1. The velocity increases with an increase in Eckert number Ec and the radiation parameter N whereas it decays with an increasing value of Hartmann number M.
2. The temperature increases with increasing values of Ec, M and N.
3. The spatial distribution of entropy for the varying values of the parameters Ec and M is peculiarly different in contrast to the parameters N and ω.
4. There is a pronounced qualitative generation in entropy adjacent to the wall that continually decays as we go move away from it.
5. The global entropy G_{Ns} increases with an increase in Ec, N and ω whereas it decreases with an increase in M.

The configuration considered here can be a single unit or a part of the larger set –up. The analysis gives us a launching pad to adopt a mechanism for entropy minimization. The work presented here testifies that the theoretical treatment to entropy generation is not only insight giving but also provides freedom to play with the parameters. It is expected that the study would serve as a pertinent introductory model for future explorations.

BOUNDARY LAYERS

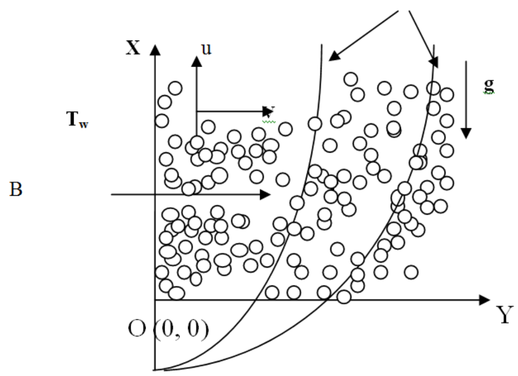

Figure 1: Schematic diagram of the problem

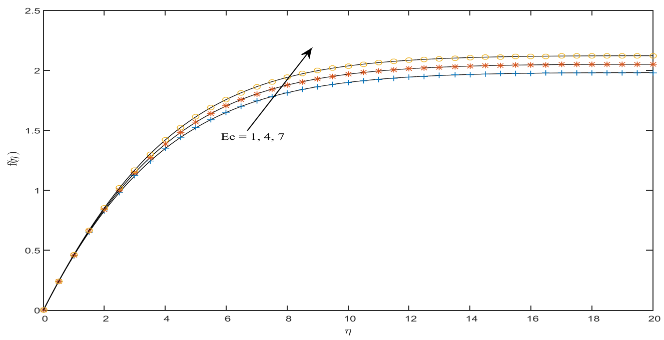

Figure 2 Velocity profiles for varying values of Ec when M= 1, N = 2.

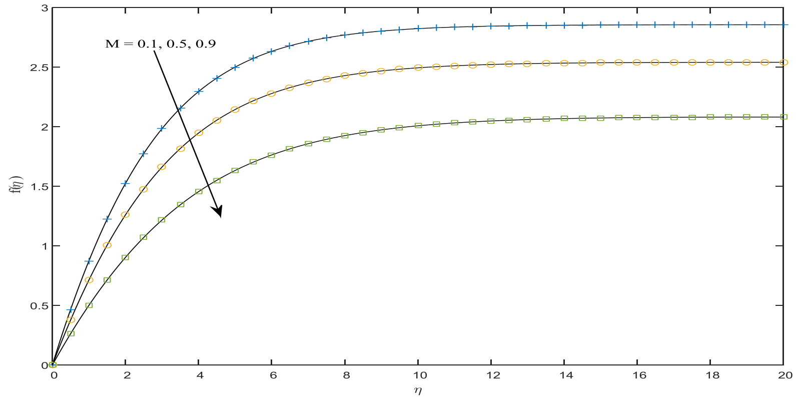

Figure 3 Velocity profiles for varying values of M when Ec = 0.6, N = 2.

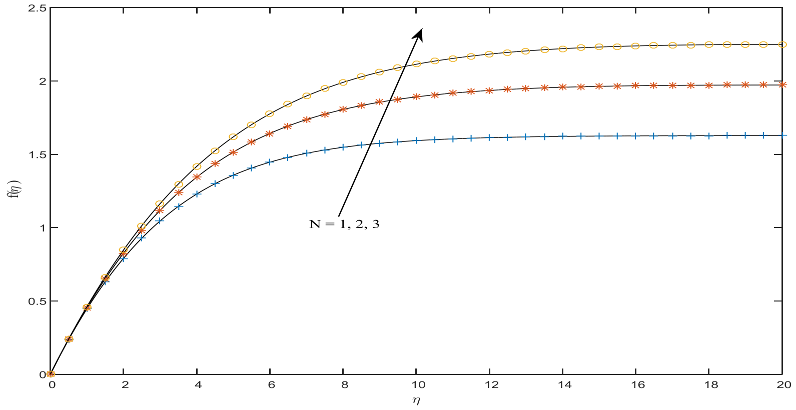

Figure 4 Velocity profiles for varying values of N when Ec = 0.6, M = 1.

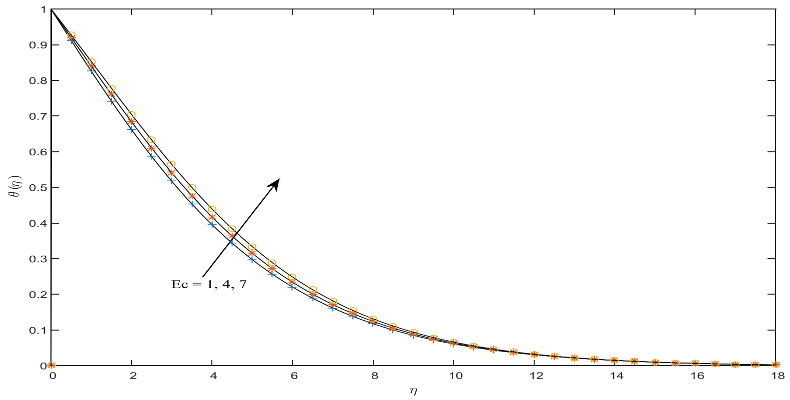

Figure 5 Temperature profiles for varying values of Ec when M = 1, N = 2.

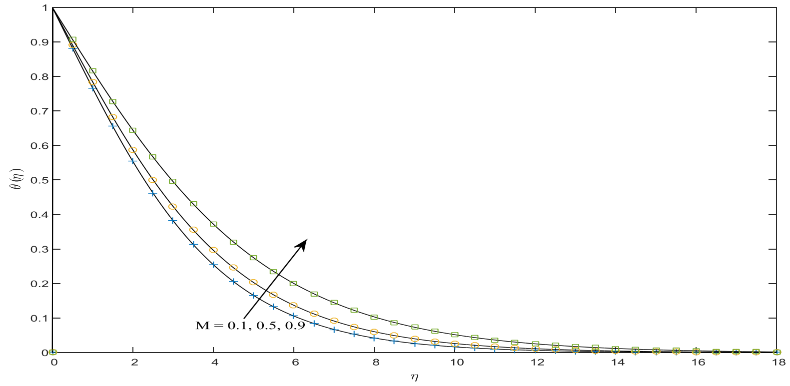

Figure 6 Temperature profiles for varying values of M when Ec = 0.6, N = 2

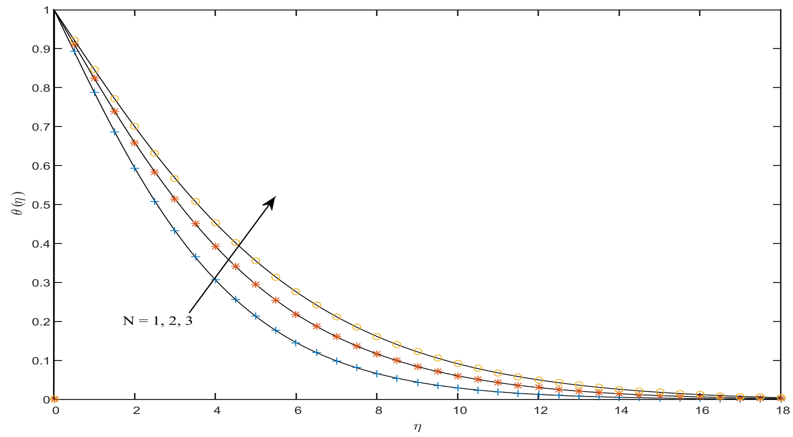

Figure 7 Temperature profiles for varying values of N when Ec = 0.6, M = 1

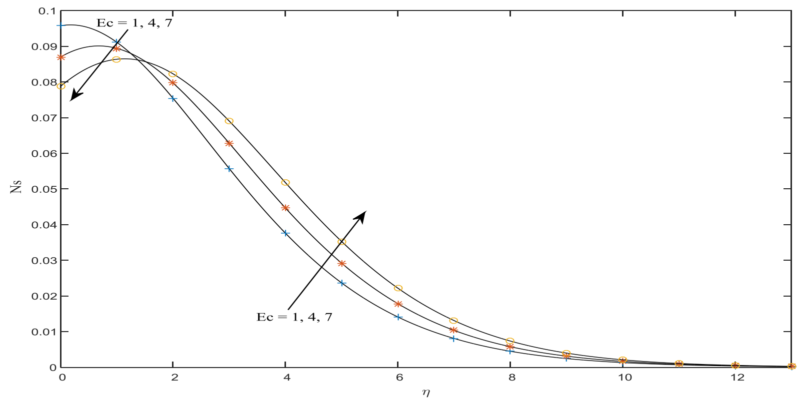

Figure 8 Entropy Generation Number for varying values of Ec when M = 1, N = 2, ω = 0.5

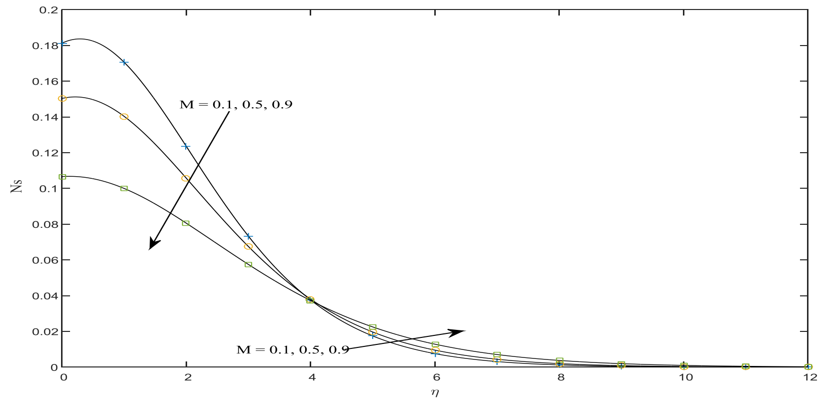

Figure 9 Entropy Generation Number for varying values of M when Ec = 0.6, N = 2, ω = 0.5.

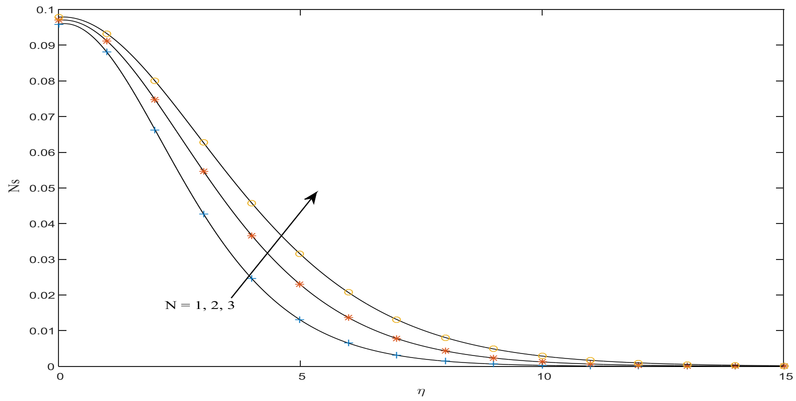

Figure 10 Entropy Generation Number for varying values of N when Ec = 0.6, M = 1, ω = 0.5.

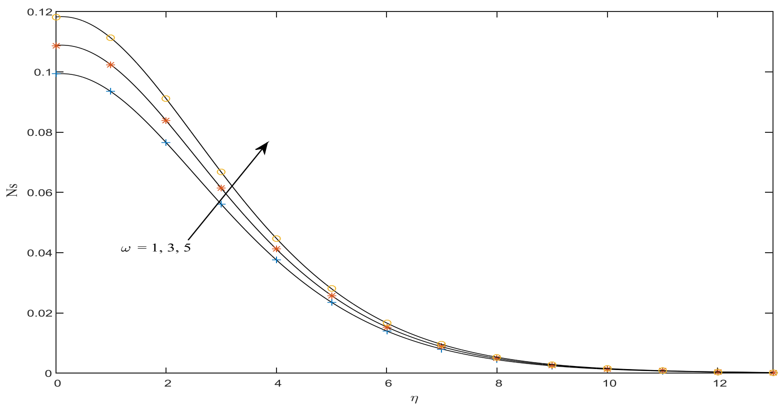

Figure 11 Entropy Generation Number for varying values of ω when Ec = 0.6, M = 1, N = 2.

Table 1	
Ec = 0.6, ω = 0.5, N = 2	
M	GNs
0.1	0.5275669478
0.5	0.4649520351
0.9	0.3792489392

Table 2	
M = 1, ω = 0.5, N = 2	
Ec	GNs
1	0.3636523944
4	0.3907301645
7	0.4162505977

Table 3	
M = 1, ω = 0.5, Ec = 0.6	
N	GNs
1	0.2953611997
2	0.3599062277
3	0.4161025431

Table 4	
M = 1, N = 2, Ec = 0.6	
ω	GNs
1	0.3686844283
3	0.4037972310
5	0.4389100338

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