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ON ENTROPY GENERATION IN RADIATIVE MHD BOUNDARY LAYER FLOW WITH PARTIAL SLIP DUE TO A MELTING SURFACE STRETCHING IN POROUS MEDIUM

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Abstract : The paper is aimed to analyse entropy generation in the radiative MHD boundary layer flow with partial slip arising due to a melting stretching sheet placed at the bottom of fluid saturated porous medium equipped with heat sink. A uniform magnetic field of strength B is assumed to be applied transversely to the sheet. The governing partial differential equations are reduced to ordinary differential equations by using similarity transformation and resulting boundary value problem is solved numerically by fourth order Runga -Kutta integration scheme together with shooting method. Effects of pertinent parameters on quantities of interest are portrayed graphically and discussed.

Keywords: Melting heat transfer, stretching sheet, entropy, heat sink, porous medium, radiation.

1. Introduction

Studies in flow and heat transfer due to continuous stretching surface are pertinent for ample practical applications in industries and technology such as drawing of plastic films and polymer sheets, etc. Pioneer study in flow due to stretching surfaces was reported by Sakiadis [27]. Afterwards, numerous studies were taken up with variety of assumptions pertaining to stretching velocity and surface temperature[1,2,6,15,20,24,26,28,30,31].

Heat transfer from a melting surface is an interesting scenario to look into for many reasons. Melting is a common feature in many natural and technological processes and it enables thermal energy storage in a melting material through a latent heat by melting process. Thus, melting can be used as a tool for optimal energy utilization. Some relevant studies have been reported in the literature. Hayat et al. [16] examined stagnation point flow of Powell-Eyring fluid towards a linear stretching surface with melting. Awais et al. [4] reported melting heat transfer in the stagnation point flow of Burgers fluid. Das [12] investigated melting heat transfer in the MHD flow over a moving surface. Yacob et al. [39] simulated melting phenomenon in boundary layer stagnation point flow of micropolar liquid over a stretching/shrinking surface. Hayat et al. [17] studied melting effects on the boundary layer stagnation point flow of third grade fluid towards a stretching surface. Bachok et al. [5] examined boundary layer stagnation point flow of viscous fluid and heat transfer with melting of a stretching sheet. Hayat et al.[18] investigated effects of melting process in the stagnation point flow of Maxwell fluid with double diffusive effect. Mustafa et al. [25] examined the characteristics of melting heat transfer in the flow of Jeffery fluid in the presence of viscous dissipation. Awais et al. [3] examined the stagnation point flow with melting phenomena in the presence of thermal diffusion and diffusion thermo effects. Several authors have also studied heat transfer with melting process to name a few [7,11,14,21,22]. However, entropy generation analysis for thermo fluidic configurations with melting aspect has received little attention. Entropy analysis is important for containing the thermodynamic irreversibility, therefore many studies have been reported in the literature to name a few [8,9,19,29,32-38]. The foregoing problem investigates the one in which boundary -layer flow and heat transfer takes place in porous medium due to a melting stretching surface. It is expected that such a study would help understand analogous systems where thermodynamic irreversibility is a challenge to take on. The findings can be used as initial estimates for larger configurations.

2. Formulation of the problem

Let us consider a steady two dimensional MHD radiative boundary- layer flow of an electrically conducting, incompressible and viscous fluid due to a linearly stretching sheet. The sheet is placed at the bottom of fluid saturated porous medium and is melting at a steady rate. The porous medium is equipped with uniform heat sink Q_0. A uniform magnetic field of strength B is assumed to be applied transversely to the sheet. The temperature of the melting surface is assumed to be T_m and that of free stream is assumed to be T_∞ ($T_\infty > T_m$). A cartesian coordinate system is assumed where x and y axes are taken along and normal to the stretching sheet respectively.

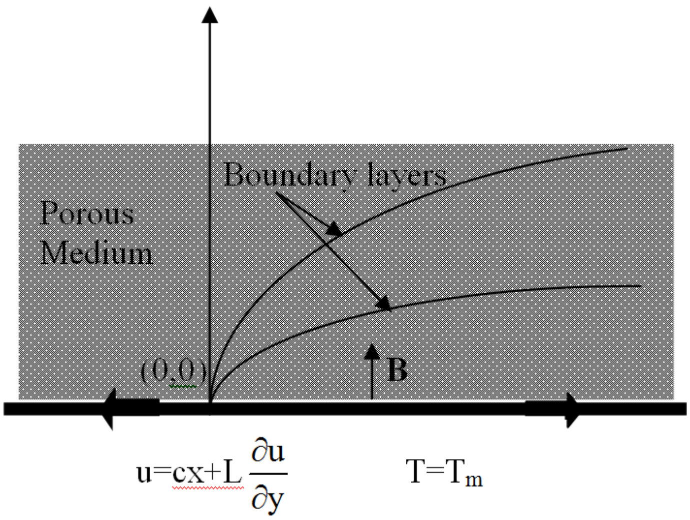

Figure 1: Sketch of the problem

The boundary-layer equations for the set up are

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\nu u}{K_0}-\frac{\sigma B^2 u}{\rho} \tag{2}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\kappa\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y}+Q_0\left(T-T_m\right) \tag{2}$$

Together with the following boundary conditions

$$\begin{aligned} &y=0: \quad u=cx+L\frac{\partial u}{\partial y},\ T=T_m \\ &y\to\infty: \quad u=0, \quad T=T_\infty \end{aligned} \tag{3}$$

$$\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}=\rho\left[\lambda+C_s\left(T_m-T_0\right)\right]v\left(x,0\right) \tag{4}$$

Here u and v are the velocity components along the x and y axes respectively. T is the fluid temperature, ν is the kinematic viscosity, K_0 is the permeability, σ is electrical conductivity, B is the magnetic field, ρ is the density of the fluid, C_p is the specific heat ,κ is the thermal conductivity of the fluid, q_r is the radiative heat flux, c is the stretching rate of the sheet, L is the slip length, λ is the latent heat of the fluid, C_s is the heat capacity of the solid surface. The equation (4) means that the heat conducted to the melting surface is equal to the heat of melting and possible heat required to raise the solid temperature T_0 to its melting temperature T_m ([10], [13]).

The radiation heat flux q_r is given as follows [23],

$$q_r=-\frac{4\gamma^*}{3\alpha^*}\frac{\partial T^4}{\partial y} \tag{5}$$

Where γ^* and α^* are Stephan-Boltzmann constant and mean absorption constant respectively. Assuming the temperature difference within the fluid sufficiently small so that T^4 may be expressed as a linear function of the temperature T and for that T^4 is expanded in a Taylor series about T_m and omitting higher order terms to yield

$$T^4=4T_m^3 T-3T_m^4 \tag{6}$$

We introduce the following non dimensional quantities

$$u = \frac{\partial \psi}{\partial y}, v = -\frac{\partial \psi}{\partial x}, \psi = (a\nu)^{1/2} x f(\eta), \eta = \left(\frac{a}{\nu}\right)^{1/2} y,$$
$$u = axf'(\eta), v = -(a\nu)^{1/2} f(\eta), \theta(\eta) = \frac{T - T_m}{T_\infty - T_m} \quad (7)$$

Where Ψ is the stream function, η is the similarity variable and prime denotes differentiation with respect to η. We see that the equation of continuity (1) is identically satisfied and equations **Error! Reference source not found.** and (2) take the following respective forms

$$f''' + ff'' - f'^2 - (M^2 + K) f' = 0 \quad (8)$$

$$(1 + N)\theta'' + \Pr f\theta' + S\theta = 0 \quad (9)$$

where

$$M^2 = \frac{\sigma B^2}{a\rho},\ K = \frac{\nu}{aK_0}, N = \frac{16\gamma^* T_m^3}{3\alpha^* \kappa},\ \Pr = \frac{\mu C_p}{\kappa}, S = \frac{Q_0 \nu}{a\kappa} \quad (10)$$

are Hartmann number, permeability parameter, radiation parameter, Prandtl Number, sink parameter respectively,

And the boundary conditions (3) and (4) become

$$\eta = 0 : f'(0) = \varepsilon + \delta f''(0), \theta = 0$$
$$\eta \to \infty : f' \to 0, \theta \to 1 \quad (11)$$
$$\Pr f(0) + Me\theta'(0) = 0$$

Where ε.=c/a is the stretching parameter (ε>0), $\delta = L(a/\nu)^{1/2}$ is the slip parameter and $Me = \frac{C_p (T_\infty - T_m)}{\lambda + C_s (T_m - T_0)}$ is the melting parameter which is a combination of Stefan numbers $C_f(T_\infty - T_m)/\lambda$ and $C_s(T_m - T_0)/\lambda$ for the liquid and solid phases respectively.

3. **Solution of the Problem**

The boundary value problem (BVP) given by (8), (9) and (11) has been solved numerically by Runge-Kutta fourth order scheme together with shooting method. The (BVP) is first converted into a system of initial value problems where systematic guesses are made for unknown quantities arising due to the conversion of BVP into system of initial value problems such that the end conditions are satisfied. For the present case the BVP is reduced to following system of initial value problems.

$$f_3' + f_1 f_3 - f_2^2 - \left(M^2 + K\right) f_2 = 0 \tag{12}$$

$$\left(1 + N\right) f_5' + \Pr f_1 f_5 + S f_4 = 0 \tag{13}$$

With initial conditions

$$f_2\left(0\right) = \varepsilon + \delta f_3\left(0\right), f_4\left(0\right) = 0, \Pr f_1\left(0\right) + Me f_5\left(0\right) = 0 \tag{14}$$

where

$$f = f_1, f' = f_2, f'' = f_3, \theta = f_4, \theta' = f_5 \tag{15}$$

The computation involved two challenges i.e. to find suitable guesses for unknown quantities f_3 (0) and f_5 (0) such that end conditions (12) are satisfied together with to find appropriate η_{max} or η_∞ . In order to ensure the accuracy of numerical code, a step size $\Delta\eta$ = 0.001 was found to be satisfactory with error tolerance of order 10^{-6} for all the cases of parameter values entering in to the problem. The computations provide velocity and thermal regimes which are readily used to compute entropy generation as discussed in the following section

4. Second law Analysis

The local volumetric rate of entropy generation S_G for the present setup is given as follows

$$S_G = \frac{\kappa}{T_\infty^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(1+N\right)\left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{\mu}{T_\infty}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{\sigma B^2 u^2}{T_\infty} + \frac{\mu u^2}{T_\infty K_0} \tag{16}$$

The equation (16) reveals that four factors contribute to entropy generation. The first term shows the contribution of heat transfer and radiation to entropy generation across boundary layer, the second term is the local entropy generation due to fluid friction, the third term is the local entropy generation due to the Ohmic dissipation and the fourth term gives the local entropy generation due to the resistance to fluid traversal offered by the porous medium.

We introduce the characteristic entropy generation rate S_{G0}, the characteristic temperature ratio ω respectively as follows:

$$S_{G0} = \frac{a\kappa(T_\infty - T_m)^2}{\nu T_\infty^2},\ \omega = \frac{T_\infty}{T_\infty - T_m} \tag{17}$$

Thus, the non-dimensional entropy generation number N_s is given by

$$N_s = \frac{S_G}{S_{G0}} = \left(1+N\right)\theta'^2 + \frac{Br\omega}{\varepsilon^2}\left[f''^2 + \left(M^2+K\right)f'^2\right] \qquad (18)$$
$$= HTI + FFI$$

where

$$Br = \frac{c^2 x^2 \mu}{\kappa\left(T_\infty - T_m\right)} \quad \left(\text{Brinkman number}\right)$$

Heat transfer irreversibility (HTI) = (1+N) θ'^2

and fluid friction irreversibility (FFI) = $\frac{Br\omega}{\varepsilon^2}\left[f''^2 + \left(M^2+K\right)f'^2\right]$

The Bejan Number Be defined as follows

$$Be = \frac{HTI}{HTI+FFI} \qquad (19)$$

is a pertinent irreversibility parameter. It takes values between 0 and 1.The values 0 and 1 for Be correspond respectively to the cases when there is no irreversibility due to heat transfer and when the irreversibility due to fluid friction is zero.

5. Results and discussion

Fig. 2 displays that entropy generation number N_s increases in the boundary layer with the increasing values of Brinkman number Br. Fig. 3 shows that N_s decreases in the boundary layer with the increasing values of δ and the trend is reversed far away from the sheet. Fig. 4 exibits that with the increasing values of ε , N_s increases and the trend reverses some where in the middle of the boundary layer region. Fig. 5 shows that the variations in entropy number with varying permeability values is not uniform across the boundary layer. This may be corrborated to the fact N_s increases upto η = 0.3 with the increasing values of permeability parameter K and beyond this spatial distance N_s decreases with an increase in K upto η=2 then again N_s increases with an increase in K in the region adjacent to the edge of the boundary layer. Here, it should be recalled that K is the reciprocal of the Darcy number. The fig.6 depicting variations in entropy for varying values of M exhibits the same phenomenon as in case of permeability parameter K. Fig. 7 shows that with an increase in Melting parameter Me, the N_s decreases upto a certain spatial distance i.e. η=1.7 and after that the trend reverses. Fig. 8 displays that entropy generation number N_s increases with the increasing values of radiation parameter N. Fig. 9 shows that entropy generation number N_s increases with the increasing values of ω. Fig. 10 displays that entropy generation number N_s initially decreases with the increasing values of sink parameter S and the trend reverses near η=2.5. Figs. 11 to Figs. 19 display variations in Bejan number Be. The figures reveal that Be varies for varying values of different parameters upto a certain spatial distances in the boundary layer and then it attains the value unity at the edge of the boundary layer. Be = 1 stands for the case when heat transfer irreversibility dominates over fluid friction irreversibility in as much as that there is no contribution of fluid friction to the irreversibility. We wish to emphasize on fig.16 which shows that Melting has a qualitative and quantitative impact on Be to the effect that at a given spatial distance η, Be decreases with increasing values of Me. Hence, we conclude that the melting rate can be a tool / aspect to be reckon with in dealing with configurations where thermodynamic efficiency is desirable. The same trend is witnessed for the case of variations in omega, sink parameter S (figs.18,19). The fig. 17 exhibits that at a given spatial distance η, Be increases with increasing values of N. The same trend is witnessed for the case of variations in ε and δ (figs. 12,13).

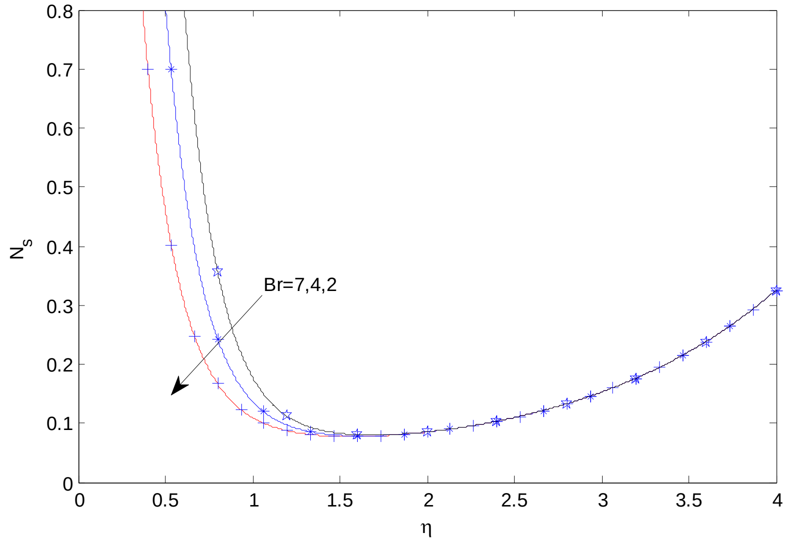

Figure 2: Entropy variation with varying Brinkman number Br, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, ω=0.4

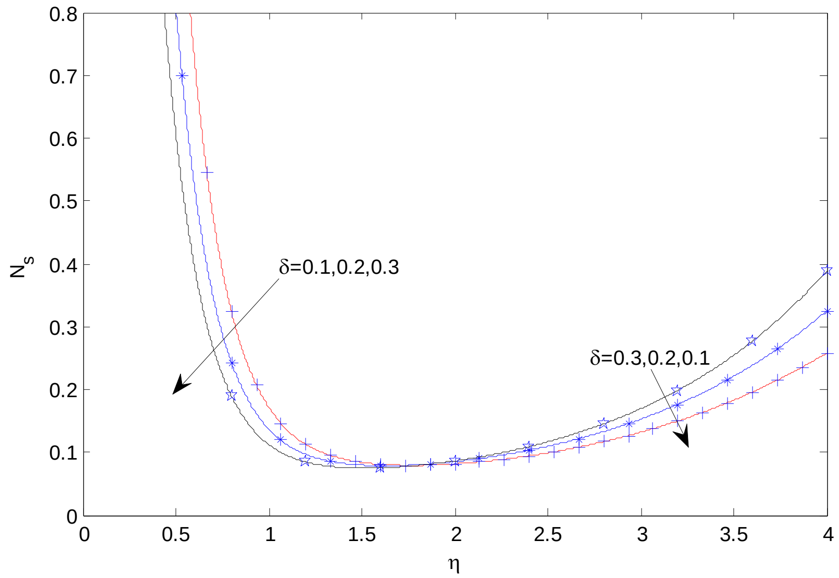

Figure 3: Entropy variation with varying δ, for M=1, Pr=8, K=5, S=–1, N=1, ε=1, Me=2, Br=4, ω=0.4

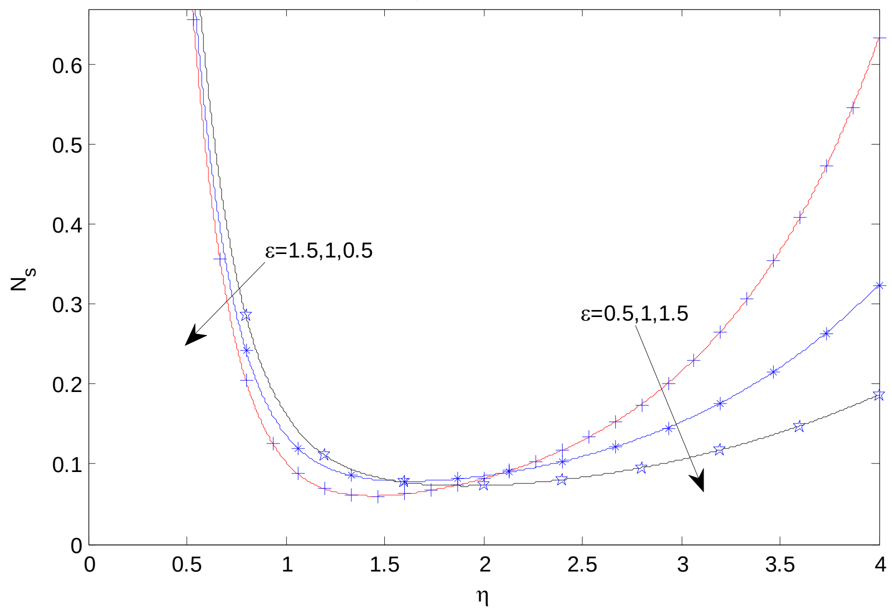

Figure 4: Entropy variation with varying ε, for M=1, Pr=8, K=5, S=–1, N=1, δ=0.2, Me=2, Br=4, ω=0.4

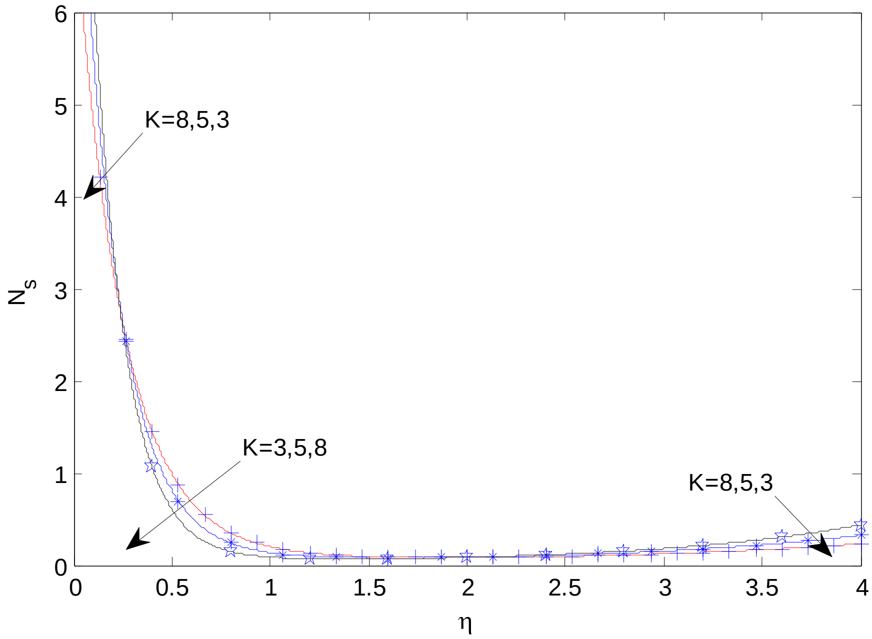

Figure 5: Entropy variation with varying K, for M=1, Pr=8, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

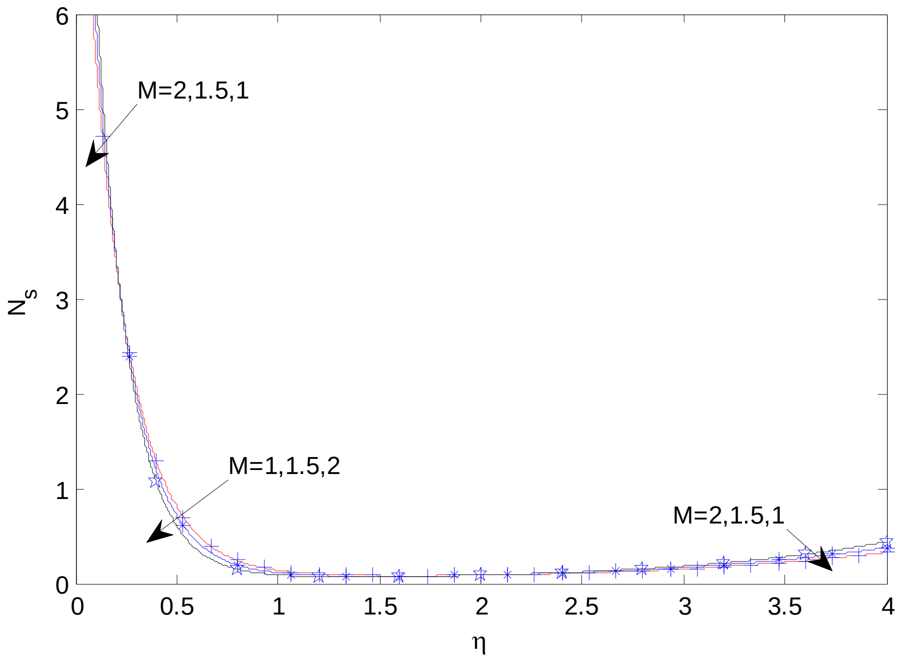

Figure 6: Entropy variation with varying M, for Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

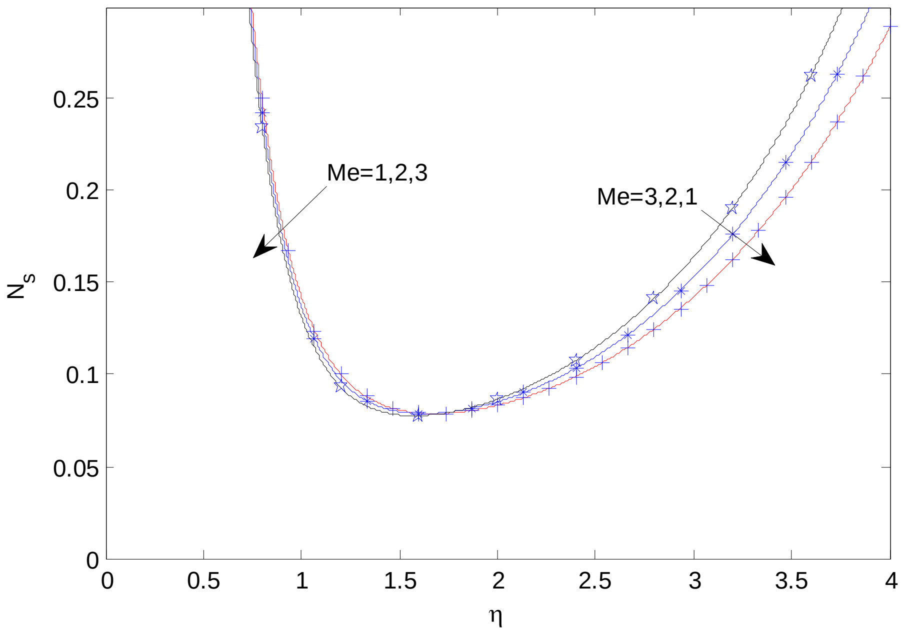

Figure 7: Entropy variation with varying Me, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2 , Br=4, ω=0.4

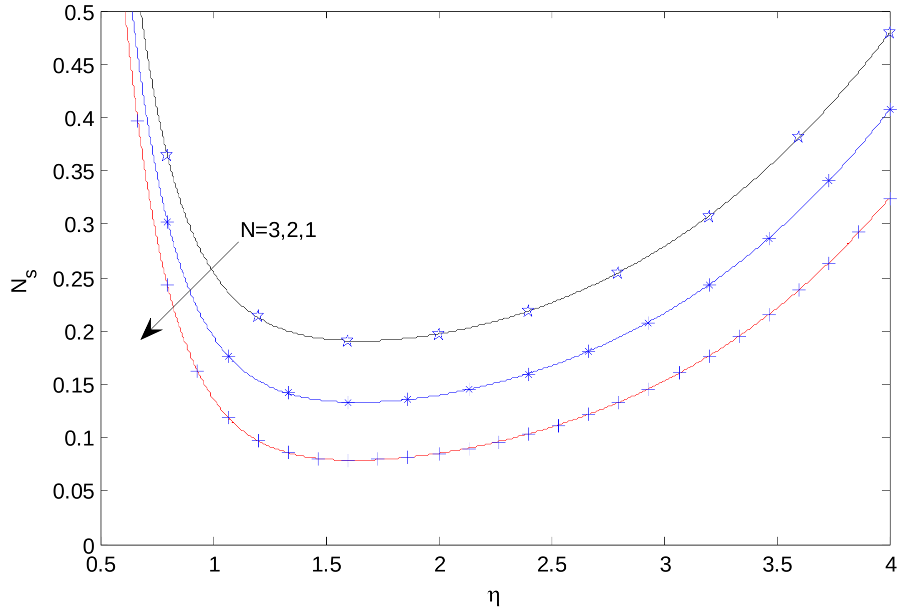

Figure 8: Entropy variation with varying N, for M=1, Pr=8, K=5, S=-1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

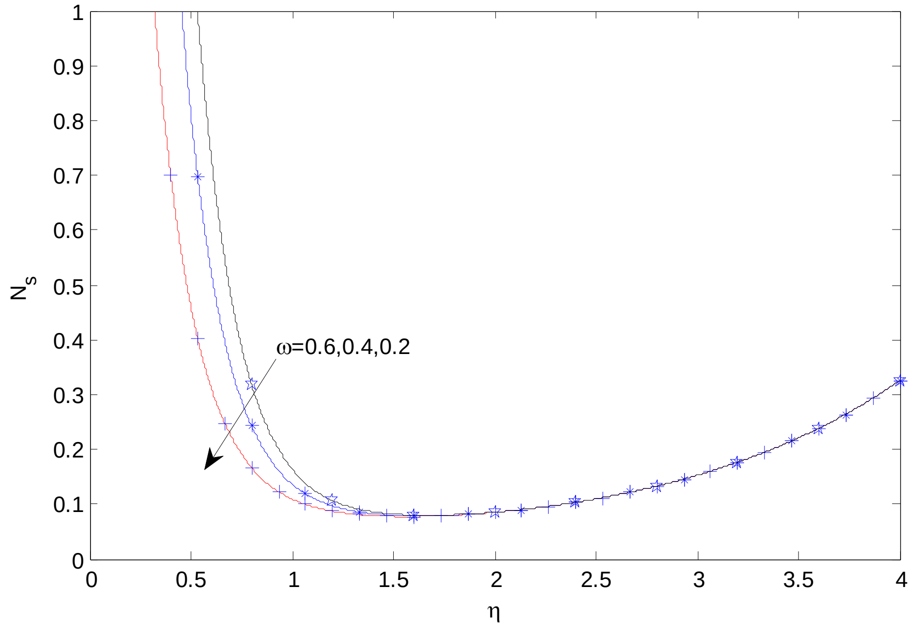

Figure 9: Entropy variation with varying ω, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4

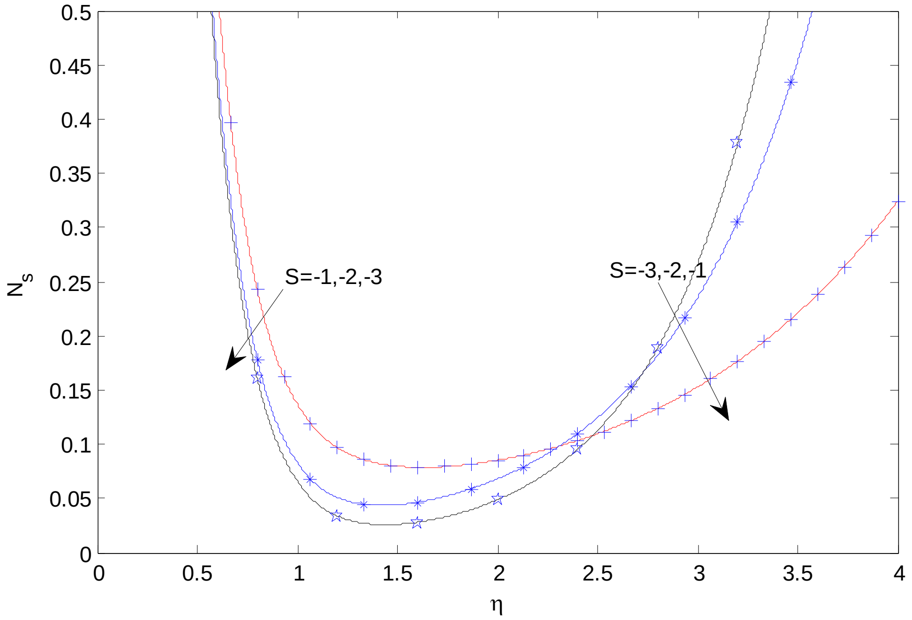

Figure 10: Entropy variation with varying S, for M=1, Pr=8, K=5, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

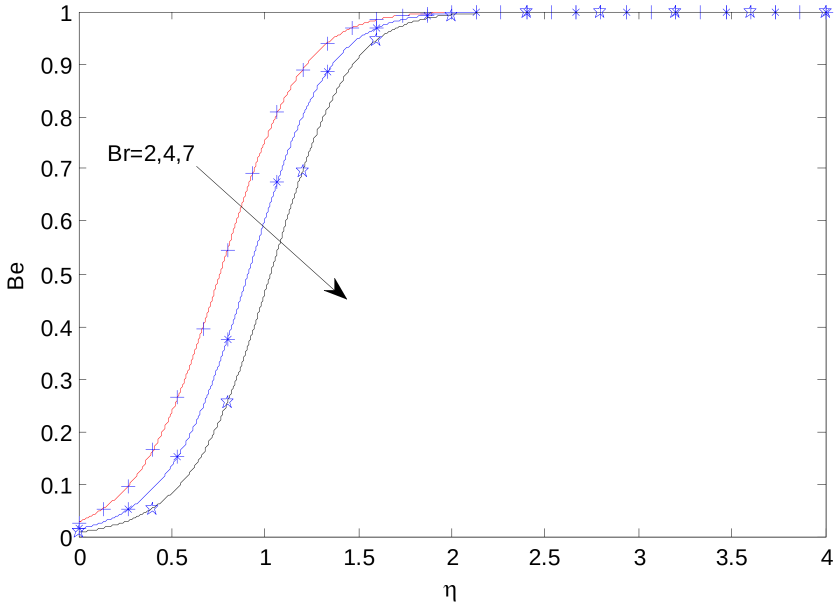

Figure 11: Bejan number variation with varying Br, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, ω=0.4

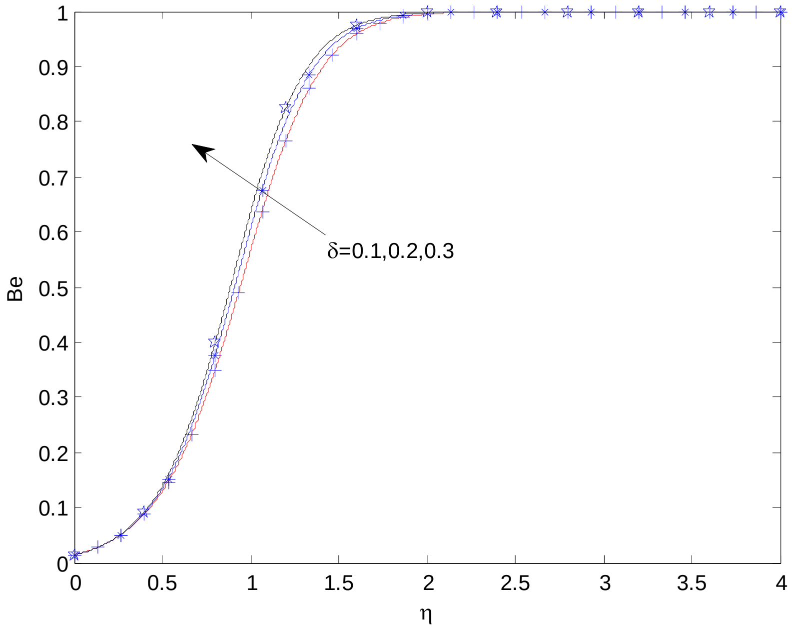

Figure 12: Bejan number variation with varying δ=0.2, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, Me=2, Br=4, ω=0.4

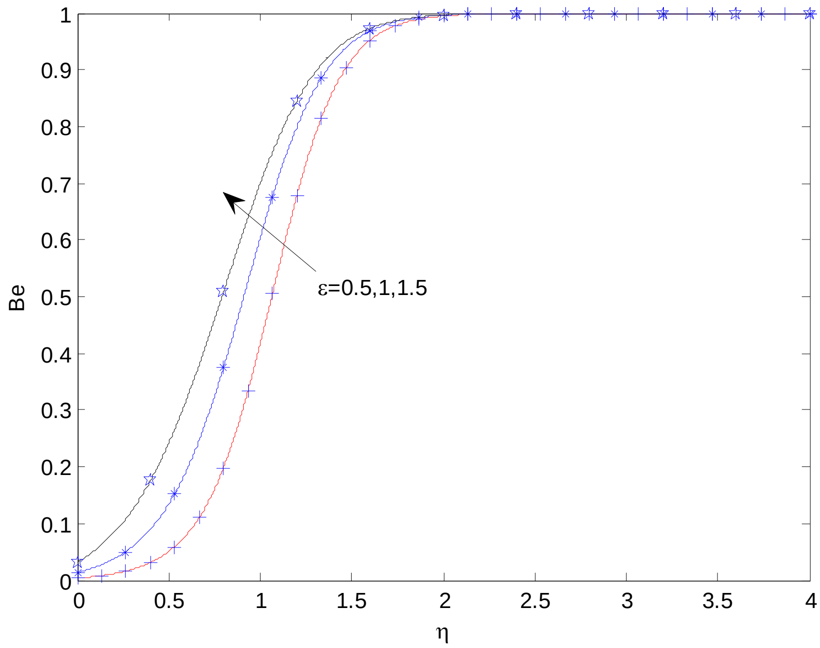

Figure 13: Bejan number variation with varying ε, for M=1, Pr=8, K=5, S=-1, N=1, δ=0.2, Me=2, Br=4, ω=0.4

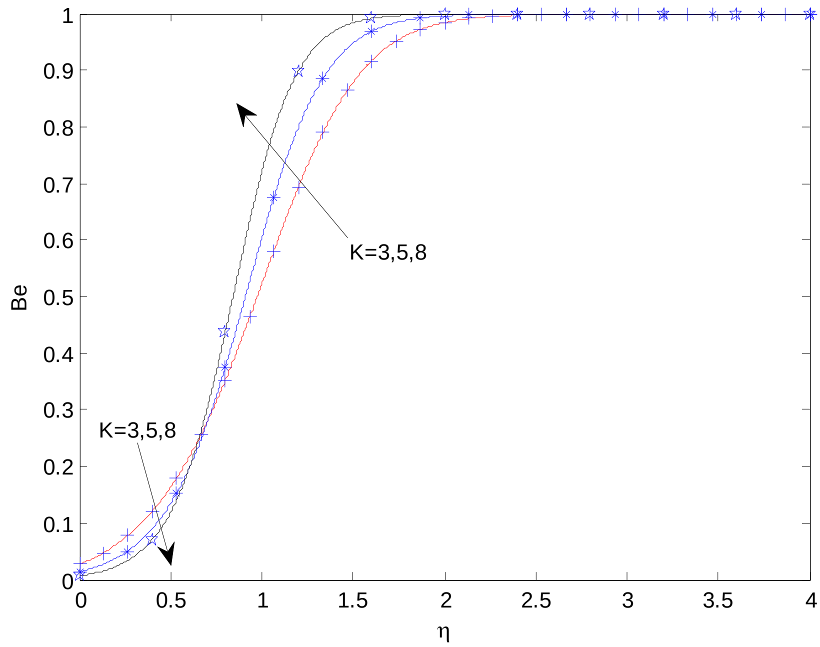

Figure 14: Bejan number variation with varying K, for M=1, Pr=8, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

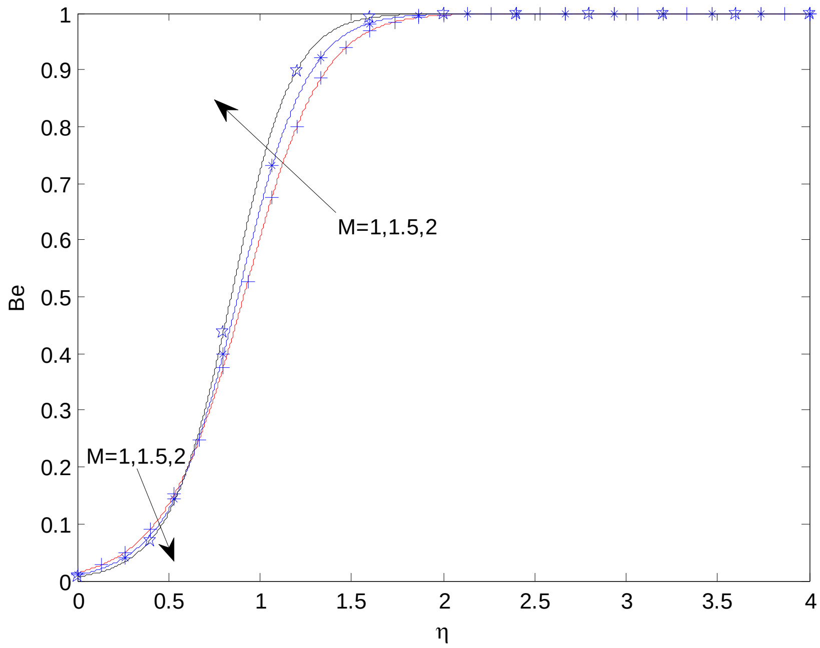

Figure 15: Bejan number variation with varying M, for Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

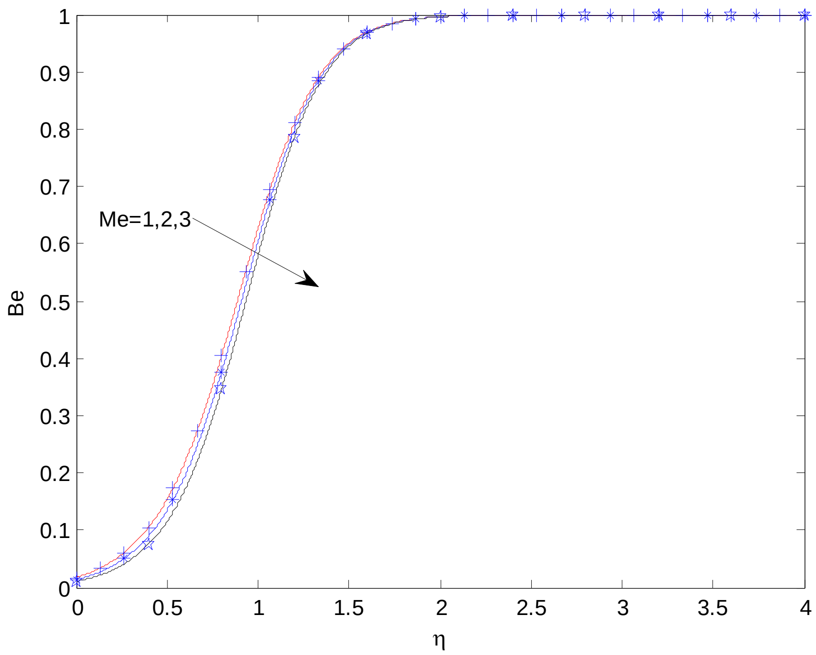

Figure 16: Bejan number variation with varying Me, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Br=4, ω=0

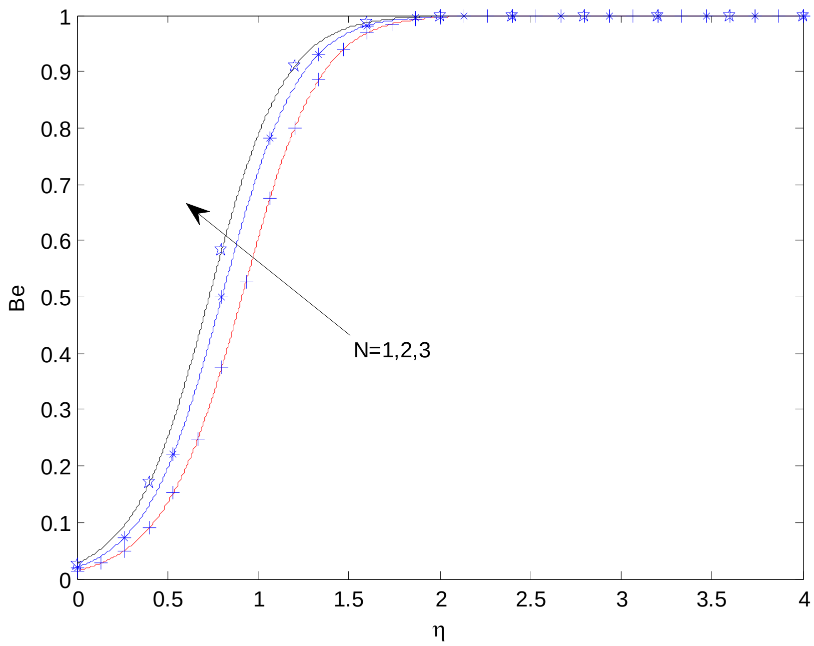

Figure 17: Bejan number variation with varying N, for M=1, Pr=8, K=5, S=-1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

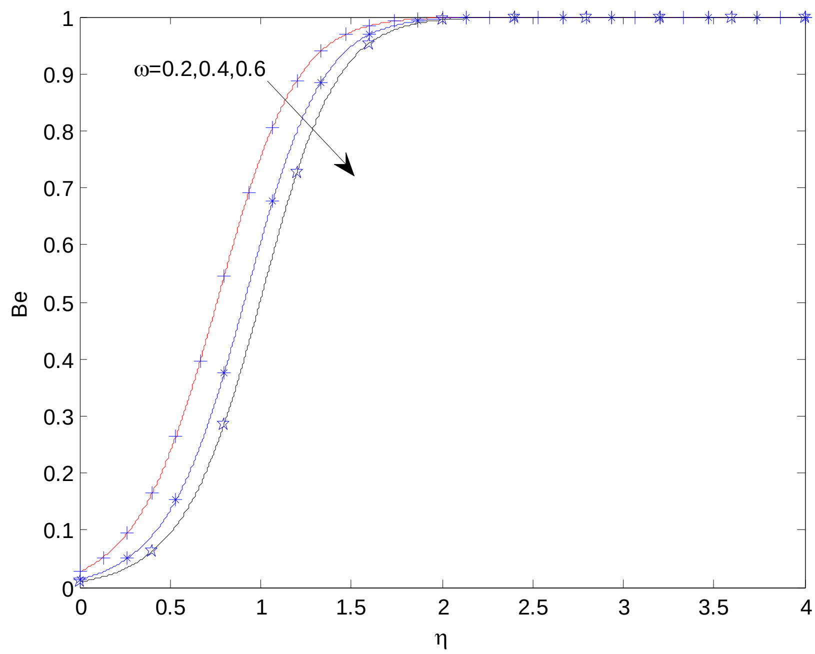

Figure 18: Bejan number variation with varying ω=0.4, for M=1, Pr=8, K=5, S=-1, N=1, ε=1, δ=0.2, Me=2, Br=4

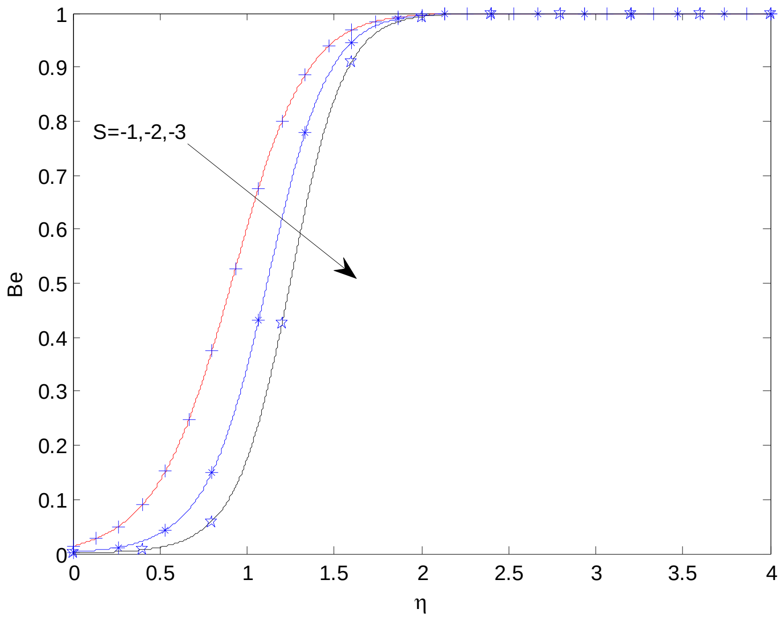

Figure 19: Bejan number variation with varying S, for
M=1, Pr=8, K=5, N=1, ε=1, δ=0.2, Me=2, Br=4, ω=0.4

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