Impact Factor (SJIF): 4.714 E-ISSN: 2583-1615

International Journal of Research in Academic World

Received: 05/December/2022 **IJRAW:** 2023; 2(1):155-164 **Accepted:** 02/January/2023

Influence of Thermal Radiation, Heat Generation, Chemical Reaction & Suction/Injection on a Three-Dimensional Flow over a Stretching Surface

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Abstract

The present work is based on the study of a three dimensional steady and laminar flow over a continuously stretching surface. This flow has been under continuous effects of heat generation, thermal radiation, concentration, and chemical reaction along with suction/injection. The governing conservation equations have been formulated and then transformed from partial differential equations to ordinary differential equations with corresponding boundary conditions using similarity transformations. The transformed equations then have been converted to first order linear differential equations. The resultant initial value problem has been solved numerically using ODE45, an inbuilt feature of MATLAB software package, which is based on Range-Kutta 4th order method or shooting method. The graphs have been plotted for various values of different parameters.

Keywords: Three-dimensional flow, laminar flow, thermal radiation, suction/injection

Introduction

Fluid Dynamics is an interesting discipline of physics having an extensive and wide range of applications in almost all fields of engineering metallurgy, astrophysics, plasma physics, geophysics and in biological processes. The study of fluid flow involving heat and mass transfer over a stretching surface with effects of concentration finds its application in several industrial processes such as metal and polymer extrusions, chemical processing equipment, heat exchangers, cooling towers, dryers, combustors, getting mass flow speed of petroleum through tubes, continuous casting, glass blowing and lots of other processes. Also, this study is applicable in manufacturing processes such as extrusion of plastic sheets, glass-fibre, paper production, food processing, hot rolling, wire drawing, crystal growing and many more processes. Fluid flow over a stretching surface produces heat and mass transfer and is also affected by difference in concentration in the presence of chemical reaction and suction/injection. Hence, this space of fluid dynamics attracts several researchers to work upon. H. Alotaibi and M.R. Eid [1] studied the Darcy-Forchheimer three-dimensional flow of permeable nanofluid through a convectively heated porous extending surface under the influences of the magnetic field and nonlinear radiation. The consequences of the surface mass transfer on natural convection flow from a vertical stretching surface and predictions on the rate of heat transfer are present in the work of S.G. Bejwada, Y.D. Reddy, K.S. Kumar, and E.R. Kumar [2]. D. Sarve, P.K. Gaur, and V.K. Sharma [3] researched on the influence of energy of activation on Darcy-Forchheimer flow of Casson fluid with nano particles over a stretching cylinder. R. Kumar, R. Mehta, K. Sharma, and D. Kumar [4] examined the impact of current energy and heat transmission properties of a 2D magnetohydrodynamic stationary Casson shear thickening liquid via a perpendicular extending pane installed in a permeable medium in the existence of a changeable warmth sink/source. The movement of Casson-Williamson Fluid under the effects of external magnetic field, thermal radiation and chemical consequences considering all the physical aspects was examined by P.P. Humane, V.S. Patil and A.B. Patil [5]. Influence of aligned magnetic field on the steady boundary layer flow and heat transfer over a stretching sheet with Newtonian heating boundary condition was studied by A R M Kasim *et al.* [6]. The study of a magneto hydrodynamic (MHD) free convection flow of an incompressible viscous fluid flow past a vertical surface by considering viscous dissipation under the influence of radiation effect and chemical reaction with constant heat and mass fluxes was conducted by B. Awasthi [7]. The squeezing flow of Copper-water and Copper kerosene between two parallel plates was analysed under the influence of magnetic field considering the effect of pressure gradient term using regular perturbation method by M.G. Sobamowo, A.T. Akinshilo [8]. S. Maity, S.K. Singh, and A.V. Kumar [9] studied three-dimensional flow of thin Casson liquid film over a porous unsteady stretching sheet under assumption of initial uniform film thickness with effects of the uniform transverse magnetic field, suction, and injection. C.S.K. Raju, N. Sandeep, and M.G. Reddy [10] analysed the effects of

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nonlinear thermal radiation on three-dimensional flow of Jeffrey fluid past a stretching/shrinking surface in the presence of homogeneous-heterogeneous reactions, non-uniform heat source/sink and suction/injection. The effects of suction/injection and chemical reaction on mass transfer characteristics over a stretching surface subjected to three dimensional flows were studied by Saad *et al.* [11]. The effects of radiation and heat generation on steady thermal boundary layer flow induced by a linearly stretching sheet immersed in an incompressible micropolar fluid with constant surface temperature were investigated by M.G. Reddy [12]. The effects of thermal radiation, heat generation, chemical reaction and suction/injection on heat and mass transfer characteristics over a stretching surface subjected to three-dimensional flow were studied by Elbashbeshy *et al.* [13]. A study of the laminar three-dimensional flow of non-Newtonian incompressible viscoelastic fluid with mass and heat transfer over an infinite horizontal stretching sheet under heat generation (absorption) and chemical reaction was done by Eldabe *et al.* [14]. R. Nazar *et al.* [15] studied the effects of viscoelastic fluid on the velocity profiles of three-dimensional flow over a stretching surface. The unsteady laminar boundary layer flow over a continuously stretching permeable surface was investigated by A. Ishak, R. Nazar and I. Pop [16]. Heat transfer in a porous medium over a stretching surface with internal heat generation and suction or injection was analyzed numerically in the presence of radiation by T. Sultana *et al.* [17]. S. Shateyi [18] investigated thermal radiation and buoyancy effects on heat and mass transfer over a semi-infinite stretching surface with suction and blowing. Aboeldahab *et al.* [19] studied the combined free convective heat and mass transfer effects on the unsteady three-dimensional laminar flow over a time dependent stretching surface, and also the impact of generation or consumption of the diffusion species due to a homogeneous chemical reaction. The thermal boundary layer on an exponentially stretching continuous surface with an exponential temperature distribution in the presence of the magnetic field effect was investigated numerically by Odat *et al.* [20]. The influences of temperature-dependent fluid properties on the boundary layers over a continuously stretching surface with constant temperature were investigated by T. Fang *et al.* [21]. Elbashbeshy *et al.* [22] studied the effect of internal heat generation and suction/injection on the flow and thermal boundary layer over a stretching surface. S.H. Takhar *et al.* [23] studied the effects of heat transfer on three dimensional MHD boundary layer flow through a stretching surface. The problem of steady, laminar, free convection flow over a vertical porous surface in the presence of a magnetic field and heat generation or absorption was considered by Chamkha [24]. The present analysis is an investigation of heat and mass transfer of a three dimensional steady and laminar flow over a stretching surface under the effects of thermal radiation, heat generation, first order chemical reaction along with suction/injection. This work can be said a study corresponding to the work of Elbashbeshy *et al.* [13].

Mathematical Model of the Problem

For the mathematical formulation of the problem, we consider a laminar, incompressible, viscous, and steady flow over a continuous stretching surface. This three-dimensional flow is under the effects of thermal radiation, heat generation, chemical reaction, and suction/injection. Within a limited range of temperature, the properties of the fluid are assumed to be constant. The fluid taken into account here is thick optical medium, therefore viscous dissipation is negligible. In contrast to other chemical species, the concentration of diffusing species is exceedingly small, and for the species present far from the surface the concentration C_∞ is also very small. The 3-D coordinate axes are defined in such a way that x and y-axis run along the plane of the stretching surface and z-axis is present perpendicular to the plane of the surface as represented in Fig. 1.

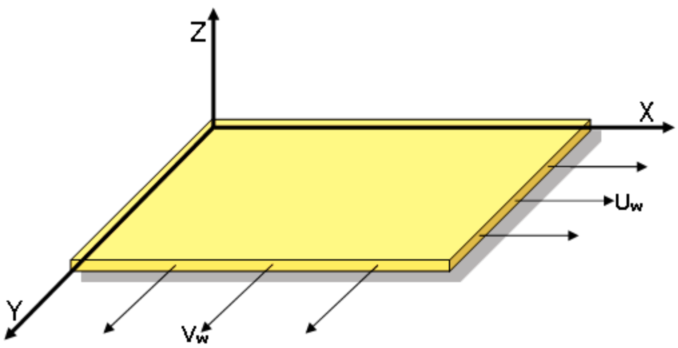

Fig 1: Geometrical Representation with Coordinate System

The governing conservation equations for the steady three-dimensional flow are as follows:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\upsilon\frac{\partial^2 u}{\partial z^2} \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\upsilon\frac{\partial^2 v}{\partial z^2} \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial z^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial z}+\frac{Q}{\rho c_p}(T-T_\infty) \tag{4}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=D\frac{\partial^2 C}{\partial z^2}-k_1(C-C_\infty) \tag{5}$$

Subjected to the boundary conditions,

$u=U_w$, $v=V_w$, $T=T_w$, $C=C_w$ at $z=0$

$$u = 0,\ v = 0,\ \frac{\partial u}{\partial z} = 0,\ \frac{\partial v}{\partial z} = 0,\ T = T_\infty,\ C = C_\infty \text{ as } z \to \infty \tag{6}$$

Where,
u, v, w are velocity components in the x, y, z directions, respectively,
υ = viscosity,
T = temperature of the fluid,
σ = electrical conductivity of fluid,
k = thermal conductivity,
ρ = density of fluid,
c_p = specific heat due to constant pressure,
Q = volumetric rate of heat generation,
C = concentration of the flow,
D = mass diffusion coefficient, and,
k_1 = reaction rate coefficient.
We have assumed that the physical properties of the fluid are constant, and the viscous dissipation is negligible. Also, here we are considering the case of thick optical medium of thickness $\tau = \alpha z \gg 1$,
∴ the Rosseland approximation for radiative heat flux can be written in simplified form as follows,

$$q_r = \frac{4\sigma}{3\alpha}\frac{\partial T^4}{\partial z} \tag{7}$$

Where,
σ = Stefan-Boltzmann constant, and
α = Mean absorption coefficient.
We assume that the temperature differences within the flow are sufficiently small, such that we can express the term T^4 as a linear function of Temperature. Hence, we expand T^4 using Taylor series about T_∞ and after neglecting higher order terms, we get

$$T^4 \cong 4TT_\infty^3 - 3T_\infty^4 \tag{8}$$

Putting equations (7) and (8) in the energy equation, eq. (4) reduces to,

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial z^2} - \frac{16\sigma T_\infty^3}{3\alpha\rho c_p}\frac{\partial^2 T}{\partial z^2} + \frac{Q}{\rho c_p}(T - T_\infty) \tag{9}$$

The stretching velocities U_w and V_w, the Temperature T_w, and Concentration C_w, are assumed to of the following forms,

$$U_w = ax,\ V_w = by,\ T_w = T_\infty + c_1 x^\beta = T_\infty + c_2 y^\beta,\ C_w = C_\infty + d_1 x^\gamma = C_\infty + d_2 y^\gamma \tag{10}$$

Where,
a and b are constants and are called stretching rate,
c_1, c_2, d_1, d_2 are constants,
β =Temperature parameter, and
γ = Concentration parameter.
Now we will introduce dimensionless functions f, g, φ and θ and the similarity variable η such that,

$$\eta = \sqrt{\frac{a}{\upsilon}}z,\ u = (ax)f'_{(\eta)},\ v = (ay)g'_{(\eta)},\ w = -\sqrt{a\upsilon}(f+g),\ \varphi_\eta = \frac{T-T_\infty}{T_w-T_\infty},\ \theta_\eta = \frac{C-C_\infty}{C_w-C_\infty} \tag{11}$$

Here, prime represents the differentiation with respect to η.
The mass conservation equation (1) is identically satisfied using (11). Also, after substituting (11) in equations (2), (3), (5) & (9), we obtain the following ODEs:

$$f''' + (f+g)f'' - f'^2 = 0 \tag{12}$$

$$g''' + (f+g)g'' - g'^2 = 0 \tag{13}$$

$$\left(\frac{4R}{3} + 1\right)\varphi'' + Pr[(f+g)\varphi' - \beta(f'+g')\varphi + (\delta\varphi)] = 0 \tag{14}$$

$$\theta'' + Sc[(f+g)\theta' - \gamma(f'+g')\theta] - L\theta = 0 \tag{15}$$

Where,

$R = \frac{4\sigma T_\infty^3}{k\alpha}$ is the Thermal Radiation Parameter,

$\delta = \frac{Q}{a\mu c_p}$ is the dimensionless Heat Source or Sink,

$Pr = \frac{\mu c_p}{k}$ is the Prandtl Number,

$Sc = \frac{\upsilon}{D}$ is the Schmidt Number, and

$L = \frac{k_1 Sc}{a}$ is the Chemical Reaction Parameter.

The corresponding boundary conditions transforms from (6) to

$$\begin{gathered} f(0) + g(0) = \lambda,\ f'(0) = 1,\ g'(0) = \zeta,\ \varphi(0) = 1,\ \theta(0) = 1 \\ f'(\infty) = 0,\ f''(\infty) = 0,\ g'(\infty) = 0,\ g''(\infty) = 0,\ \varphi(\infty) = 0,\ \theta(\infty) = 0 \end{gathered} \tag{16}$$

Where,

λ = Suction/Injection Parameter $\begin{cases} (\lambda > 0), \text{ Suction, and} \\ (\lambda < 0), \text{ Injection} \end{cases}$

$\zeta = \frac{b}{a}$ is the Stretching Ratio Parameter, $\begin{cases} (\zeta = 0) \Rightarrow (g = 0), \text{Two dimensional case} \\ (\zeta = 0) \Rightarrow (f = g), \text{Axisymmetric flow} \end{cases}$

Solution Methodology

In order to solve the Equations we will convert the higher order DEs from (12) to (15) into a system of linear equations of first order, using the following variable labeling,

$S_1 = f,\quad S_2 = f',\quad S_3 = f'',\quad S_4 = g,\quad S_5 = g',$

$S_6 = g'',\quad S_7 = \varphi,\quad S_8 = \varphi',\quad S_9 = \theta,\quad S_{10} = \theta'$

The transformed equations are as follows,

$$\begin{aligned} S_1' &= S_2 \\ S_2' &= S_3 \\ S_3' &= S_2^{\,2} - (S_1 + S_4)S_3 \\ S_4' &= S_5 \\ S_5' &= S_6 \\ S_6' &= S_5^{\,2} - (S_1 + S_4)S_6 \\ S_7' &= S_8 \\ S_8' &= -\left(\frac{3Pr}{4R+3}\right)[(S_1 + S_4)S_8 - \beta(S_2 + S_5)S_7 + \delta S_7] \\ S_9' &= S_{10} \\ S_{10}' &= -Sc[(S_1 + S_4)S_{10} + \gamma(S_2 + S_5)S_9] + LS_9 \end{aligned} \tag{17}$$

The corresponding transformed initial conditions are,

$$\begin{gathered} S_1(0) + S_4(0) = \lambda,\quad S_2(0) = 1,\quad S_3(0) = m,\quad S_5(0) = \zeta, \\ S_6(0) = n,\quad S_7(0) = 1,\quad S_8(0) = h,\quad S_9(0) = 1,\quad S_{10}(0) = k \end{gathered} \tag{18}$$

Here, m, n, h, and k are unknowns that will be guessed for satisfying the max. conditions $S_2(\eta_{max}) = 0$, $S_5(\eta_{max}) = 0$, $S_7(\eta_{max}) = 0$ and $S_9(\eta_{max}) = 0$ while specifying the initial conditions for ODE45 solver in MATLAB.

Different values for the Stretching Ratio Parameter (ζ), the Suction/Injection Parameter (λ), the Thermal Radiation Parameter (R), the Dimensionless Heat Source/Sink (δ), and the Chemical Reaction Parameter (L) are taken into consideration and results for Velocity, Temperature Gradient and Concentration Gradient are studied and corresponding graphs are plotted with the help of MATLAB.

Also, we have considered different values of Prandtl Number (Pr) and Schmidt Number (Sc) and studied the corresponding results and graphs.

For the above computations, we have taken $\beta = \gamma = 2$, the temperature and concentration parameters respectively.

Results and Discussions

The impact of increasing and decreasing values of the Stretching Ratio Parameter (ζ), the Suction/Injection Parameter (λ), the Thermal Radiation Parameter (R), the Dimensionless Heat Source/Sink (δ), the Chemical Reaction Parameter (L), the Prandtl Number (Pr), and the Schmidt Number (Sc) and fixed values of Temperature Parameter ($\beta = 2$) and Concentration Parameter ($\gamma = 2$) on the dimensionless Velocity, Temperature and Concentration of the 3D flow over the stretching surface are depicted with the help of graphs in the following figures.

The following figures, Fig. 2, Fig. 3 & Fig. 4 depict that Velocity, Temperature and Concentration decreases on increasing the value of Stretching Ratio Parameter (ζ). We observe that the values of these dimensionless functions are higher for two-dimensional problem ($\zeta = 0$) in comparison to values for three-dimensional problem ($\zeta \neq 0$).

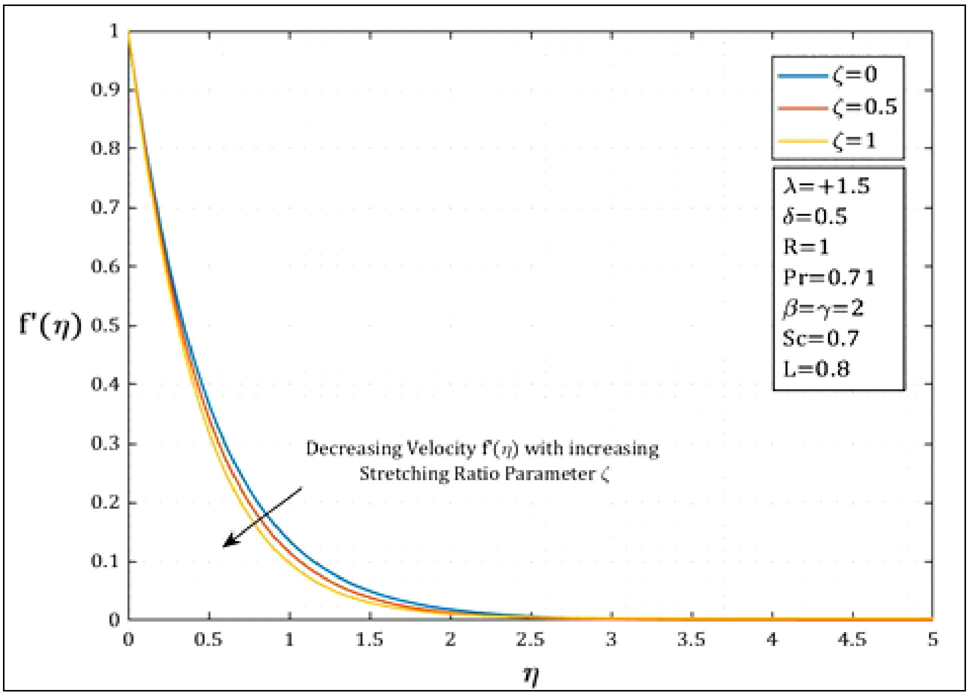

Fig 2: The Velocity plot (f'(η) vs η) under effect of increasing Stretching Ratio Parameter (ζ)

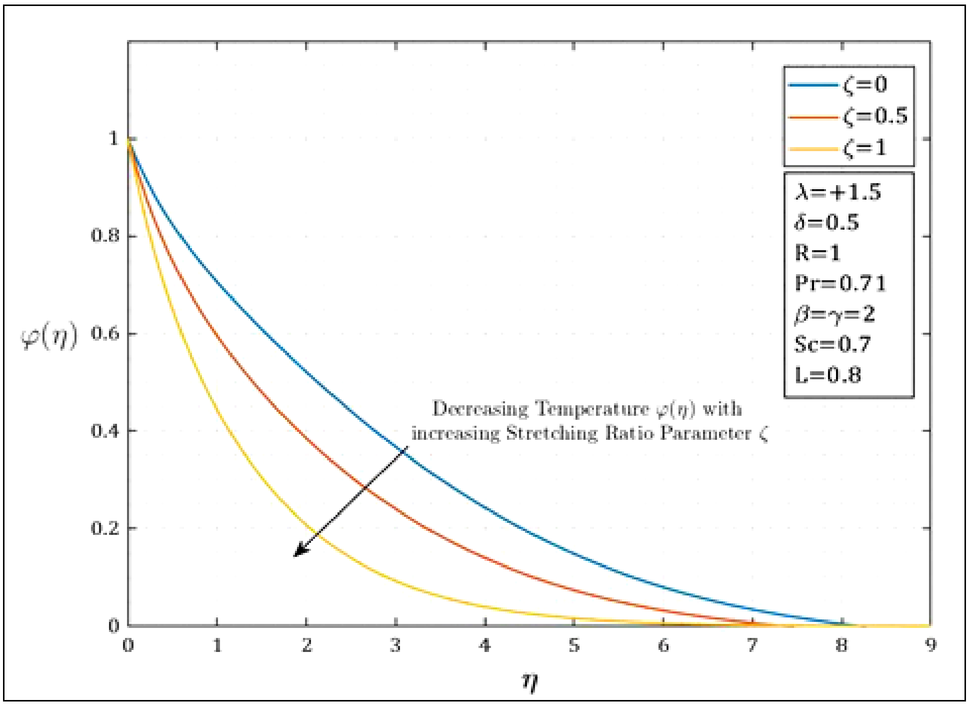

Fig 3: The Temperature plot (φ(η) vs η) under effect of increasing Stretching Ratio Parameter (ζ)

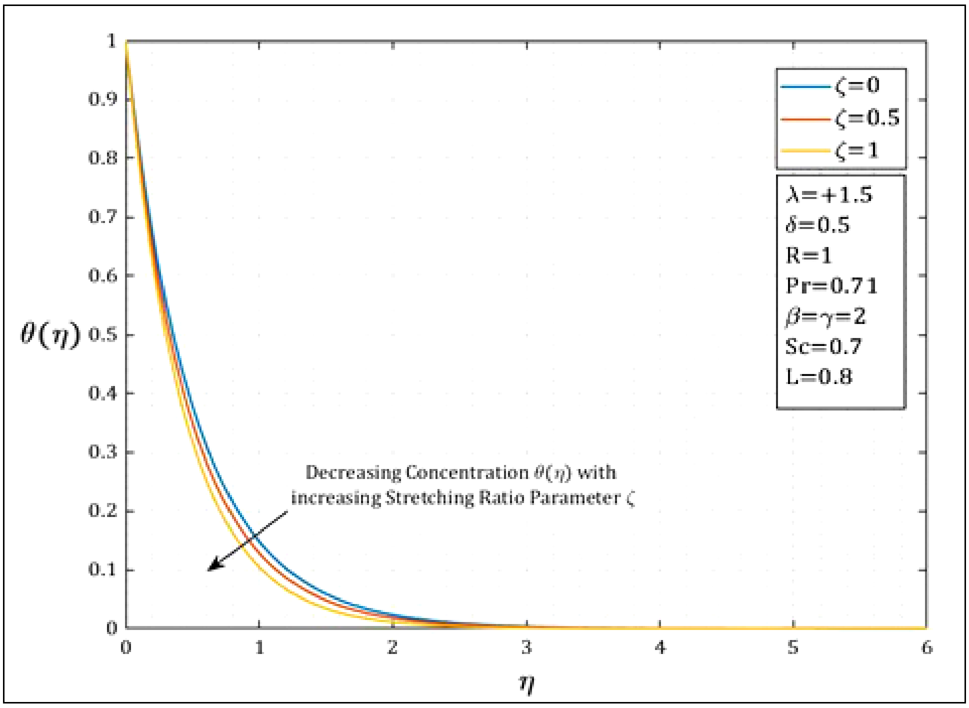

Fig 4: The Concentration plot (θ(η) vs η) under effect of increasing Stretching Ratio Parameter (ζ)

The next two figures, Fig. 5 and Fig. 6, show the decreasing Velocity and Concentration respectively under the effect of increasing values of Suction/Injection Parameter (λ). We see that the values for both the functions are higher for injection ($\lambda < 0$) than that for suction ($\lambda > 0$)

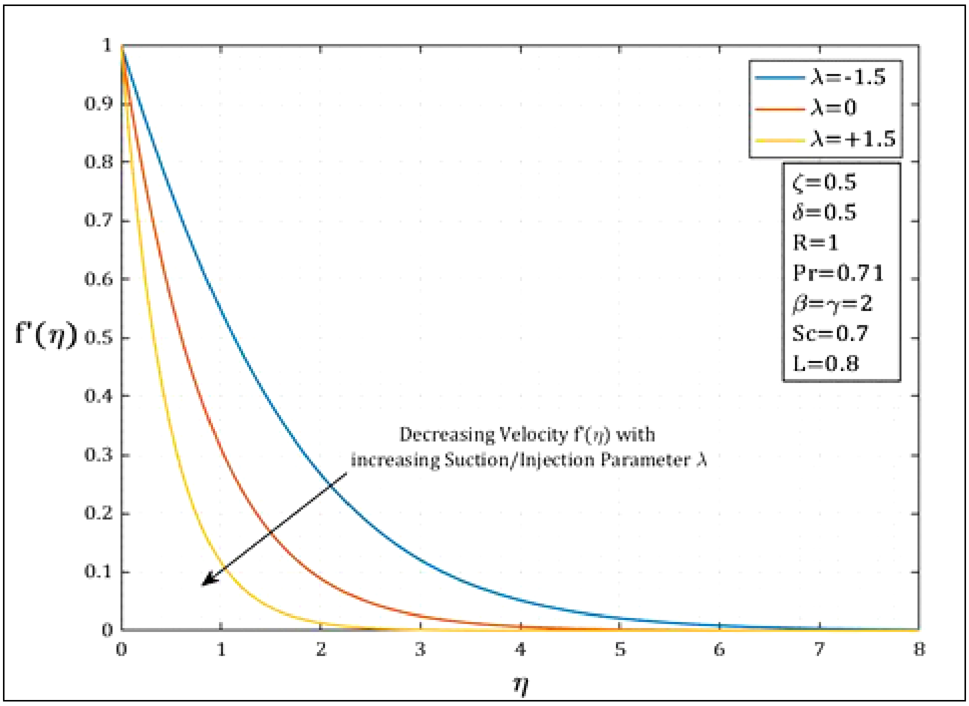

Fig 5: The Velocity plot (f'(η) vs η) under effect of increasing Suction/Injection Parameter (λ)

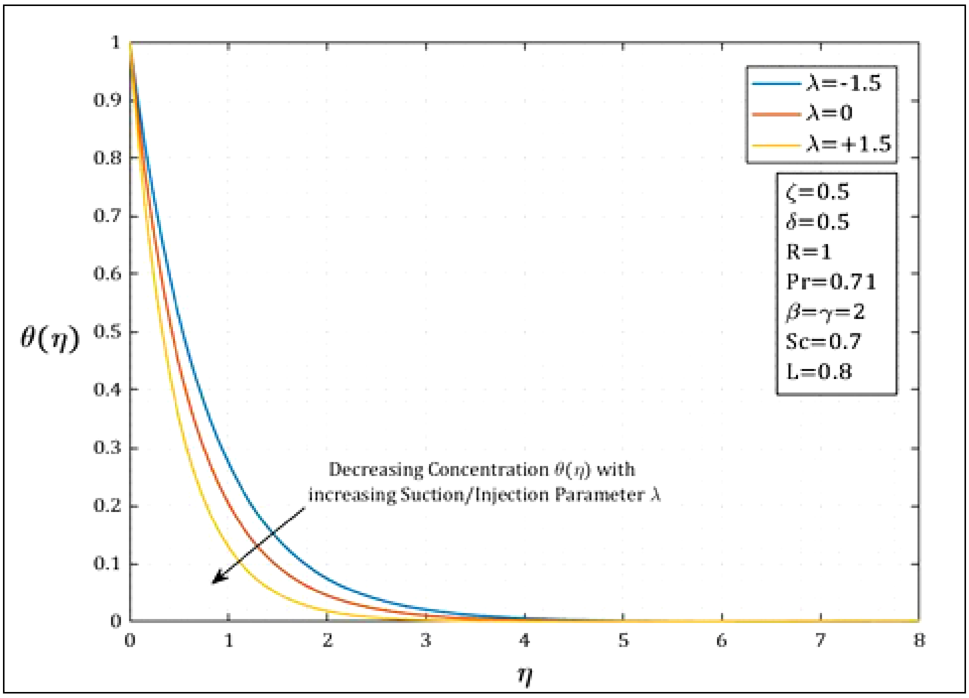

Fig 6: The Concentration plot (θ(η) vs η) under effect of increasing Suction/Injection Parameter (λ)

The Fig. 7 shows that the Temperature increases in the effect of increasing Thermal Radiation Parameter (R) producing an increase in thermal boundary condition of the flow.

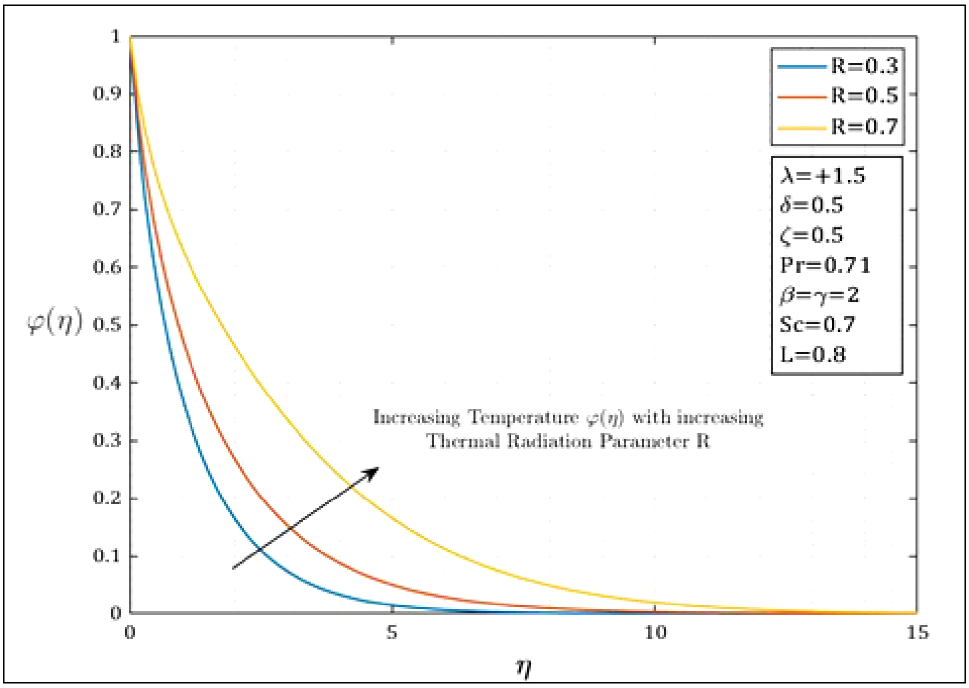

Fig 7: The Temperature plot (φ(η) vs η) under effect of increasing Thermal Radiation Parameter (R)

The Fig. 8 represents that the Temperature increases with increasing Heat Source/Sink parameter (δ) and is higher for heat source than for sink.

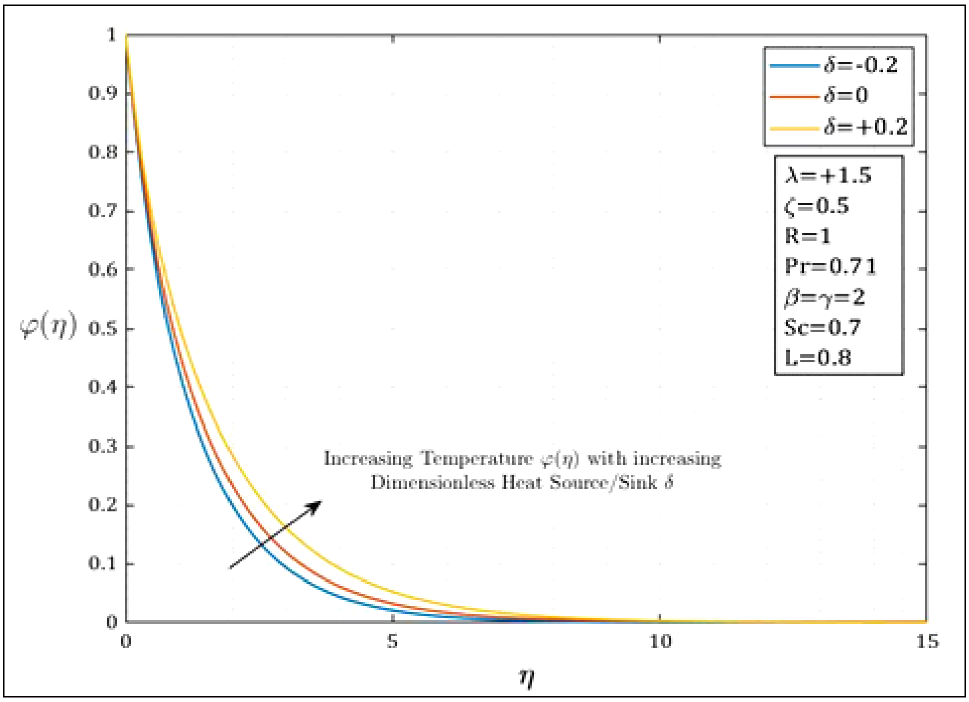

Fig 8: The Temperature plot (φ(η) vs η) under effect of increasing Dimensionless Heat Source/Sink Parameter (δ)

The Fig. 9 illustrates that the Temperature decreases on increasing the Prandtl Number (Pr) which indicates that there is a direct effect of the type of flow on boundary layer temperature

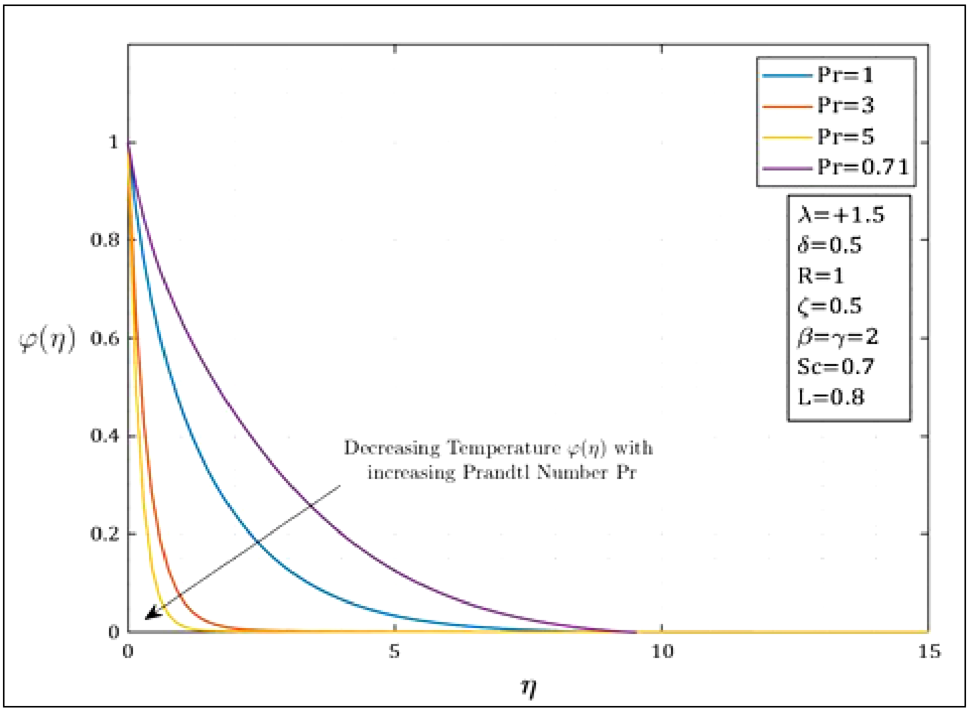

Fig 9: The Temperature plot (φ(η) vs η) under effect of increasing Prandtl Number (Pr)

The Fig. 10 depicts the decreasing Concentration on increasing the Chemical Reaction Parameter (L).

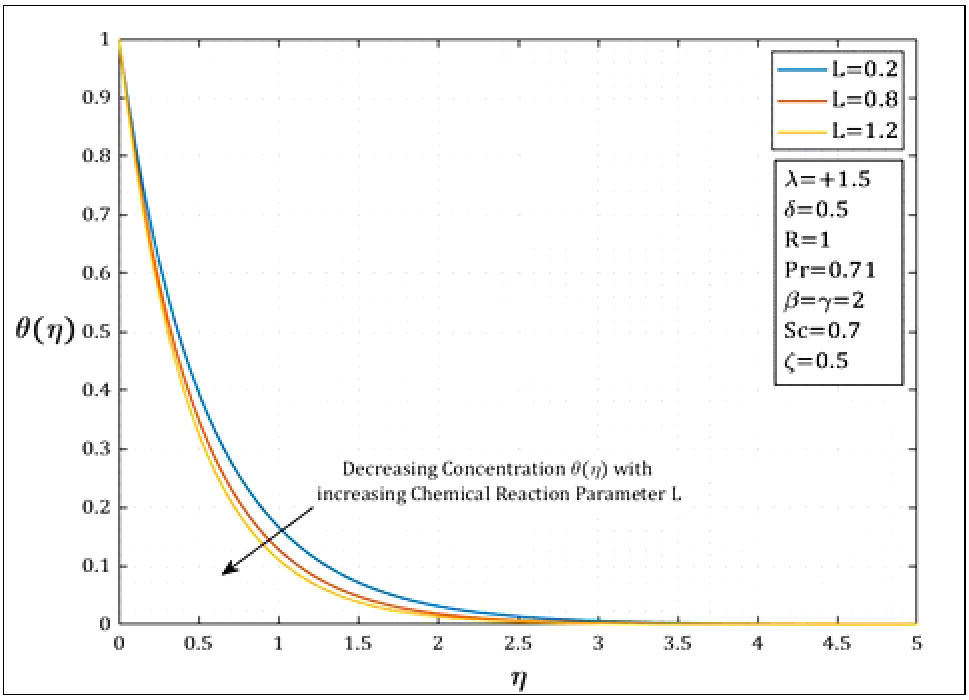

Fig 10: The Concentration plot (θ(η) vs η) under effect of increasing Chemical Reaction Parameter (L)

The Fig. 11 shows the decreasing Concentration with increasing Schmidt Number (Sc). This is the effect of different diffusing chemical species having Schmidt Number ranging from 0.1 to 1.0.

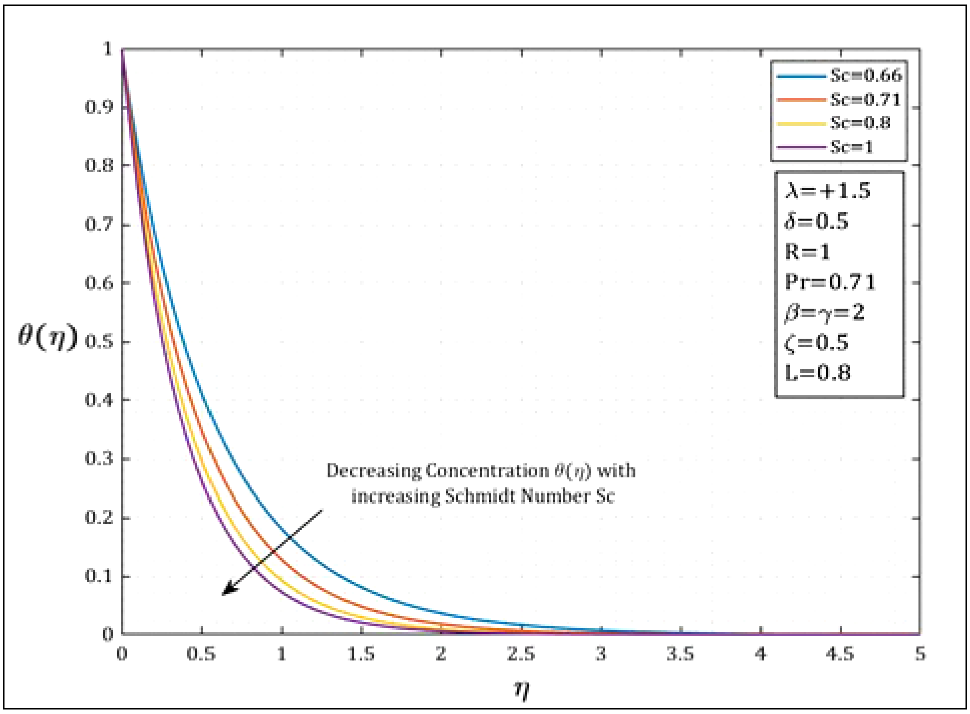

Fig 11: The Concentration plot (θ(η) vs η) under effect of increasing Schmidt Number (Sc)

Conclusion

In view of the numerical solutions obtained and the resulting graphs representing the effects of the Stretching Ratio Parameter (ζ), the Suction/Injection Parameter (λ), the Thermal Radiation Parameter (R), the Dimensionless Heat Source/Sink (δ), the Chemical Reaction Parameter (L), the Prandtl Number (Pr), and the Schmidt Number (Sc) on Velocity, Temperature and Concentration of the considered three-dimensional flow on a continuous stretching surface, we can say that Thermal Radiation, Heat Generation, Chemical Reaction and Suction/Injection have considerable effects on the mass and heat transfer characteristics, i.e., on the Velocity, flow temperature and concentration of the 3-D flow.

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