International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 2, pp 86-93, February-2022

https://doi.org/10.47001/IRJIET/2022.602015

Effects of Soret and Dufour on Mixed Convection over a Cone in a Non-Darcy Porous Medium with Chemical Reaction

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***Abstract* - This work explore the boundary layer behavior under the effects of Soret and Dufour on the mixed convection adjacent to inverted cone immersed within non-Darcian porous milieu together with chemical reaction action. The natural and forced convection limits are also considered in this study. The equations governing the problem together with the boundary conditions are converted to non-similar non-dimensional shape and solved numerically using finite difference method. It was found that enhances the value of the Soret number will increase the amount of heat transport and decrease the amount of mass transport. Enhances the value of Dufour number or chemical reaction parameter will reduce the amount of heat transfer and raise the amount of mass transfer.**

Keywords: Mixed convection, Soret effect, Dufour effect, Chemical reaction effect, Porous medium, Non-similarity solution, Heat and mass transfer, Inverted cone.

I. INTRODUCTION

In the heat transfer processes mixed convection flow over different geometrical shapes play significant role. Transport processes in porous materials have many engineering applications like thermal insulation, chemical reactor engineering, petroleum resources extraction, nuclear waste disposal, metal processing, solar collectors etc. The effectiveness of constant side mass flux on free convection flow of non-Newtonian fluids along a cone in porous medium was explored by Yih [1]. Mixed convection flow problem along a cone in porous media was analyzed numerically by Yih [2]. Radiation leverages on the combined convection along cone of constant surface temperature in porous medium together with Rosseland diffusion parataxis is examined numerically by Yih [3]. With existence of heat source/sink and magnetic flux influences, concurrent heat and mass transfer by free convection along a porous cone within porous matrix was considered by Chamkha et al. [4].

The case of free convection adjacent a cone in porous milieu stacked with a non-Newtonian fluid together with source of heat was analyzed by Grosan et al. [5]. Duwairi et al. [6] considered magneto hydrodynamic combined convection flow over anisothermal cone in porous medium. Mahdy et al. [7] study the impact of magnetic flux on the natural convection about constant surface temperature wavy cone in porous matrix. Ghalambaz et al. [8] solve the case of natural convection along a cone embedded within porous medium using power series-pade. Awad et al. [9] presented study on convection from a cone embedded in porous media under the effects of cross-diffusion. Chamkha and Rashad [10] presented a study about natural convection flow over a permeable cone immersed in a nanofluid-saturated porous milieu and with lateral mass flux.

Noghrehabadi et al. [11] study the issue of natural convection non-Darcian flow adjacent to a cone in porous media stacked through nanofluid. Makanda et al. [12] study free convection current from a cone embedded in a porous media appeased with a viscoelastic fluid. Kaya [13] investigated numerically the issue of mixed convection along a cone in high porosity porous medium together with radiation-conduction impacts. Rosali et al. [14] present analysis to study the problem of mixed convection past a cone in porous medium with convective boundary condition. Huang [15] investigates the case of heat and mass transfer in natural convection current of non-Newtonian fluid adjacent to a vertical porous cone in a porous medium with the presence of heat source, Soret, and Dufour effectiveness. Along a cone in a non-Darcian porous media, Kairi et al. [16] study the impacts of viscous dissipation and thermo-diffusion on double diffusive free convection non-Newtonian fluid.

In this paper the effectiveness of Soret and Dufour upon heat and mass transfer by mixed convection along a cone embedded in a non-Darcy porous media with the effect of chemical reaction will be studied. The whole region of combined convection is taken into consideration in this study. In other words: from pure free convection limit passing through mixed convection until reaching to pure forced convection limit. Numerical modeling and analysis of such problems are used to a large degree because the experimental work is costly and need more time. This type of studies is

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Volume 6, Issue 2, pp 86-93, February-2022
https://doi.org/10.47001/IRJIET/2022.602015

capable of providing specific understanding of the physics of such situations. This study finds applications in geothermal and geophysical engineering fields such as extraction of geothermal energy, circulation of chemical pollutant in saturated soil, underground elimination of nuclear junk, emigration of humidity in insulation. To the best knowledge of the author no previous study in the literature has assessed such problem therefore the present results are original and novel.

II. ANALYSIS

Assume the flow is non-Darcy, two dimension, steady, laminar, viscous, incompressible, and the physical properties are uniform except for the density in buoyancy term. The porous matrix is similar, isotropic, and in local thermal balance. Figure 1 depicts the shape of the cone and the coordinate axes. Furthermore, Within the boundary layer it will be assumed that $v << u,\ \partial/\partial x << \partial/\partial y$. The buoyancy force in the normal direction to the cone surface is neglected, this assumption is considered correct for a broad extent of cone angle excepting close to $\gamma = 90°$ and when $\gamma \to 0°$. Under the aforementioned assumptions and using the Boussinesq equation, the equations that represent the momentum, energy, and solute transport can be written as follows:

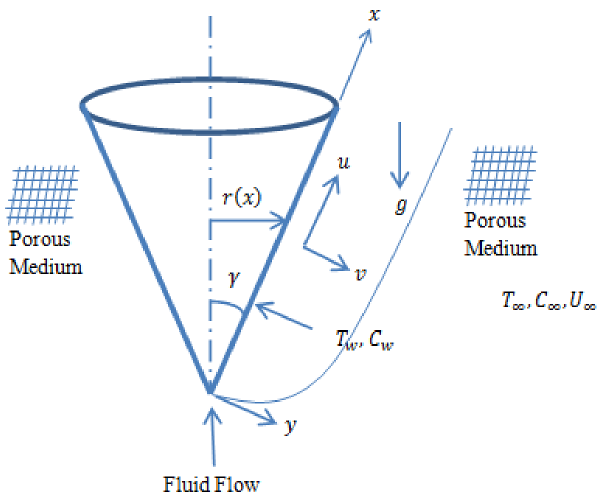

Figure 1: Sketch of a vertical cone and axes system

2.1 Continuity Equation [2]

$$\frac{\partial(ru)}{\partial x} + \frac{\partial(rv)}{\partial y} = 0 \quad (1)$$

2.2 Momentum Equation [2,17]

$$\left(1 + \frac{2c\sqrt{K}}{\nu}u\right)\frac{\partial u}{\partial y} - \frac{g\cos\gamma\, K}{\nu}\left(\beta_T\frac{\partial T}{\partial y} + \beta_C\frac{\partial C}{\partial y}\right) = 0 \quad (2)$$

2.3 Energy Equation [15,19]

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left[(\alpha + \alpha_d)\frac{\partial T}{\partial y}\right] + \frac{Dk_T}{c_s c_p}\frac{\partial 2C}{\partial y^2} \quad (3)$$

2.4 Concentration Equation [15,18]

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial 2C}{\partial y^2} + \frac{Dk_T}{T_m}\frac{\partial 2T}{\partial y^2} - k_1(C - C_\infty) \quad (4)$$

Where $r(x) = x\ \sin\gamma$ represent the local radius as shown in Figure 1, u and v are the elements of velocity in the x and y axes respectively. g is the acceleration as a result of gravity, K is permeability of the porous medium, c is the inertia coefficient, ν is the fluid kinematic viscosity, β_T *and* β_C are the expansion coefficients of thermal and concentration. C and T are the concentration and temperature, α represent the thermal diffusivity of the fluid, α_d represent the dispersion thermal diffusivity defined by $(\alpha_d = \Gamma\, u\, d)$, where the value of Γ lies between $1/7$ and $1/3$[19] and d is the pore diameter. D perform the mass diffusivity, k_T perform the ratio of thermal diffusion, c_s perform the concentration susceptibility, c_p symbolize the specific heat, T_m symbolize the mean fluid temperature, k_1 represent a constant of chemical reaction rate of first-order.

2.5 Boundary Conditions [2]

$$y = 0 \quad v = 0 \quad T_w = T_\infty + A_1 x^\lambda C_w = C_\infty + A_2 x^\lambda$$

$$y \to \infty \quad u = U_\infty = Bx^m \quad T = T_\infty \quad C = C_\infty \quad (5)$$

In the above equation the subscripts w and ∞ represents the conditions at the surface of the cone and far-off the surface respectively. A_1, A_2, B, and λ are constants, m is the parameter of the cone angle. Hess and Faulkner [20] give a tabulated values of γ and m. By defining the stream function as $ru = \partial\psi/\partial y$ and $rv = -\partial\psi/\partial x$, the equation of continuity is satisfied spontaneous. Introducing the next non-dimensional variables [2]:

$$\zeta = \left[1 + \left(\frac{Ra_x}{Pe_x}\right)^{1/2}\right]^{-1} \quad \eta = \frac{y}{x}Pe_x^{1/2}\zeta^{-1} \quad (6)$$

$$\psi = \alpha r Pe_x^{1/2} f(\zeta,\eta)\zeta^{-1}\theta(\zeta,\eta) = \frac{T - T_\infty}{T_w - T_\infty}$$

$$\Phi(\zeta,\eta) = \frac{C - C_\infty}{C_w - C_\infty} \quad (7)$$

Into the Eqs. (2)-(5), the following non-similar system of equations are obtained:

2.6 Dimensionless Form of Momentum Equation

$$(1 + 2If')f'' - (1 - \zeta)^2(\theta' + N\Phi') = 0 \quad (8)$$

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2.7 Dimensionless Form of Energy Equation

$$(1+\Gamma D_s f')\theta'' + \left[\Gamma D_s f'' + \left\{\frac{1}{2}(1-\zeta)(\lambda-m)+\frac{(m+3)}{2}\right\} f\right]\theta' - \lambda f'\theta = \frac{(m-\lambda)}{2}\zeta(1-\zeta)\left[f'\frac{\partial\theta}{\partial\zeta}-\frac{\partial f}{\partial\zeta}\theta'\right]$$

$-D_f\Phi''$ (9)

2.8 Dimensionless Form of Concentration Equation

$$\frac{1}{Le}\Phi'' + \left[\frac{1}{2}(1-\zeta)(\lambda-m)+\frac{(m+3)}{2}\right] f\Phi' - (C_r+\lambda f')\Phi = \frac{(m-\lambda)}{2}\zeta(1-\zeta)\left[f'\frac{\partial\Phi}{\partial\zeta}-\frac{\partial f}{\partial\zeta}\Phi'\right] - S_r\theta'' \quad (10)$$

Where ζ is the mixed convection parameter, η is the pseudosimilarity variable. f, θ, and Φ are the non-dimensional stream function, temperature, and concentration. $I = c\sqrt{K}\,\alpha\left(Pe_x^{1/2}+Ra_x^{1/2}\right)^2/\nu x$ represent the inertia effect parameter, $N = \beta_C A_2/\beta_T A_1$ represent the buoyancy ratio, $D_s = d\left(Pe_x^{1/2}+Ra_x^{1/2}\right)^2/x$ represent the thermal dispersion parameter, $D_f = Dk_T(C_w-C_\infty)/c_s c_p\alpha(T_w-T_\infty)$ is Dufour number, $Le = \alpha/D$ is Lewis number, $S_r = Dk_T(T_w-T_\infty)/T_m\alpha(C_w-C_\infty)$ is Soret number, $C_r = k_1x^2/\alpha\left(Pe_x^{1/2}+Ra_x^{1/2}\right)^2$ symbolize the parameter of chemical reaction, $Pe_x = U_\infty x/\alpha$ symbolize the local Peclet number, $Ra_x = g\cos\gamma\beta_T(T_w-T_\infty)Kx/\nu\alpha$ symbolize the local Rayleigh number.

2.9 Dimensionless Form of Boundary Conditions

$$\eta = 0 f(\zeta,0) = 0 \theta(\zeta,0) = 1 \Phi(\zeta,0) = 1$$

$$\eta \to \infty f'(\zeta,\infty) = \zeta^2 \theta(\zeta,\infty) = 0 \Phi(\zeta,\infty) = 0 \quad (11)$$

The primes in Eqs. (8)-(11) represents the differentiation with respect to η. The value of the mixed convection parameter ζ, is ranged from 0 (the limit of refined natural convection) to 1 (the limit of refined forced convection). Finally the important physical quantities of interest that cover the local Nusselt and Sherwood numbers and the velocity components can be given by:

$$\frac{Nu_x}{Pe_x^{1/2}\zeta^{-1}} = -[1+\Gamma D_s f'(\zeta,0)]\theta'(\zeta,0) (12)$$

$$\frac{Sh_x}{Pe_x^{1/2}\zeta^{-1}} = -\Phi'(\zeta,0) (13)$$

$$u = \frac{U_\infty}{\zeta^2} f' (14)$$

$$v = -\frac{\alpha}{x}Pe_x^{1/2}\frac{1}{\zeta}\left\{\frac{1}{2}[(1-\zeta)(\lambda-m)+(m+3)]f + \left[\frac{1}{2}(\zeta(m-\lambda)+\lambda+1)-1\right]\eta f' + \frac{(m-\lambda)}{2}\zeta(1-\zeta)\frac{\partial f}{\partial\zeta}\right\} \quad (15)$$

III. NUMERICAL SOLUTION METHOD

The numerical scheme to obtain the solution of the Eqs. (8)-(10) together with Eq. (11) is based on several concepts. Briefly two iteration processes depend on the successive substitution along with implicit tri-diagonal finite-difference method was used. The domain of interest (ζ,η) is divided into unequal spaced mesh where $\Delta\eta = 0.01$ and $\Delta\zeta = 0.05$. η_{max} is used instead of $\eta = \infty$ in Eq. (11) where η_{max} is appropriate large value of η at which Eq. (11) is satisfied. For more details see Gorla and Kumari [21].

IV. RESULTS AND DISCUSSIONS

So as to check the precision of the results to be given in this section, a rapprochement between formerly published results on a particular issue of the problem (Darcy solution) and the present results [$\lambda = 0$, $m = 0.4241237$ ($\gamma = 60°$), $I = 0$, $N = 0$, $\Gamma = 0$, $Le = 1$, $D_s = 0$, $D_f = 0$, $S_r = 0$, and $C_r = 0$] is tabulated in Table 1. The table shows that there are a good agreement between the two.

Table 1: Comparison of local Nusselt number values between present work and Yih (2001) for Darcy solution

ξ	Present work	Yih (2001)
0.0	0.7688	0.7686
0.1	0.7232	0.6997
0.2	0.6633	0.6496
0.3	0.6335	0.6228
0.4	0.6249	0.6222
0.5	0.6406	0.6480
0.6	0.6787	0.6975
0.7	0.7365	0.7661
0.8	0.8103	0.8491
0.9	0.8972	0.9427
1.0	1.0446	1.0440

In this section it will be presented the results that reflect the impacts of Soret number ($S_r = 0.3, 0.6, 1$), Dufour number $\left(D_f = 0.4,0.8,1\right)$, and chemical reaction parameter ($C_r = 0.5,1,1.5$) on the three profils (hydrodynamic, temperature, and concentricity) in addition to local Nusselt and Sherwood numbers. The values of the other parameters are fixed in this way: $\lambda = 0.5$, $m = 0.1156458$ ($\gamma = 30°$), $I = 1$, $N = 1$, $\Gamma = 0.3$, $Le = 1$, $D_s = 1$. Increasing the value of the Soret number gives rise to increasing the fluid velocity and the momentum boundary layer thickness, decreasing the fluid temperature and the thermal boundary layer thickness, and increasing the concentration of the fluid and concentration boundary layer thickness as drawn in Figures 2-4.

ISSN (online): 2581-3048
Volume 6, Issue 2, pp 86-93, February-2022
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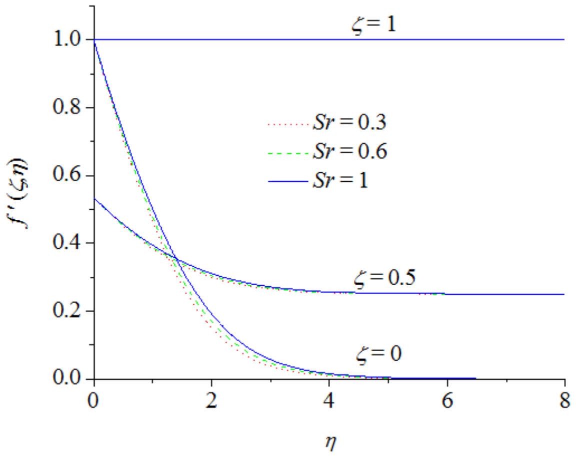

Figure 2: Behavior of fluid velocity for distinct mixed convection parameter (ζ) and Soret number (S_r) values

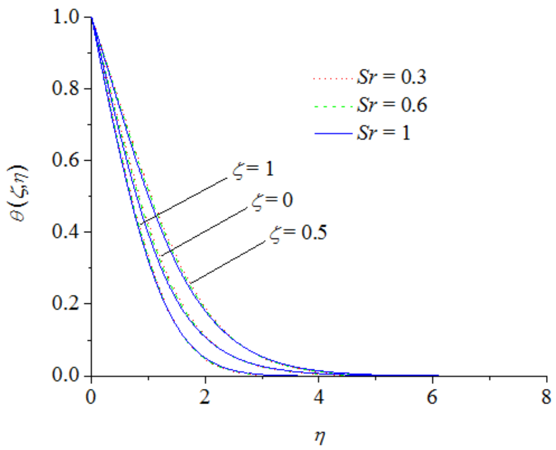

Figure 3: Behavior of fluid temperature for distinct mixed convection parameter (ζ) and Soret number (S_r) values

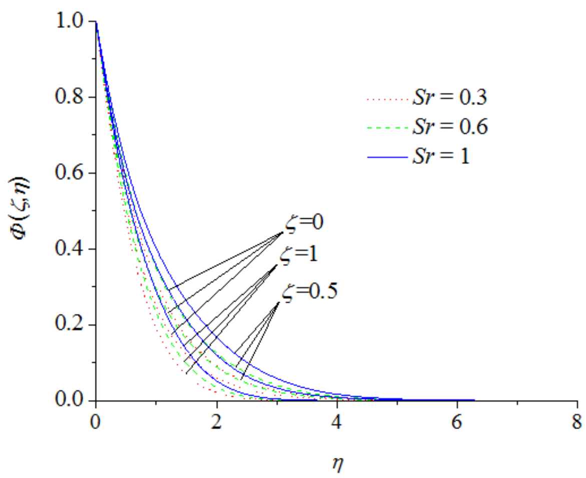

Figure 4: Behavior of fluid concentration for distinct mixed convection parameter (ζ) and Soret number (S_r) values

The variations of local Nusselt and Sherwood numbers with the non-similarity parameter are presented in Figures 5 and 6. It can be see that the grow in the value of Soret number drives to increase in the local Nusselt number value and a noticeable decrease in the local Sherwood number value. This result is due to the growth in the Soret number leads to increasing fluid velocity, increasing in the temperature gradient, and decreasing in the concentration gradient (i.e. rising the heat transfer rate and lessening the mass transfer rate).

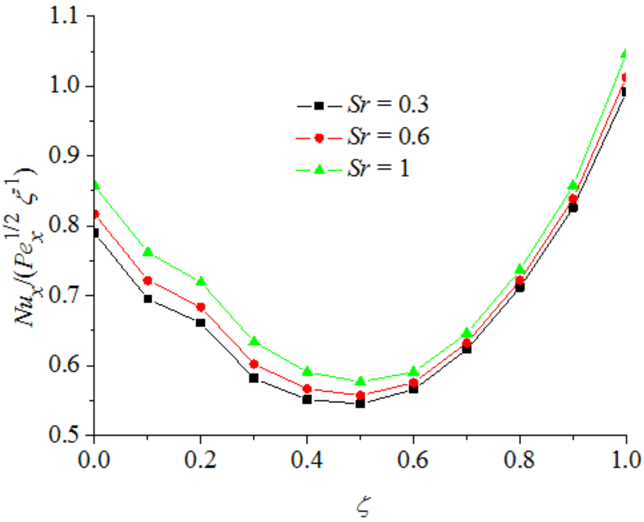

Figure 5: Behavior of Local Nusselt number for distinct amounts of Soret number (S_r)

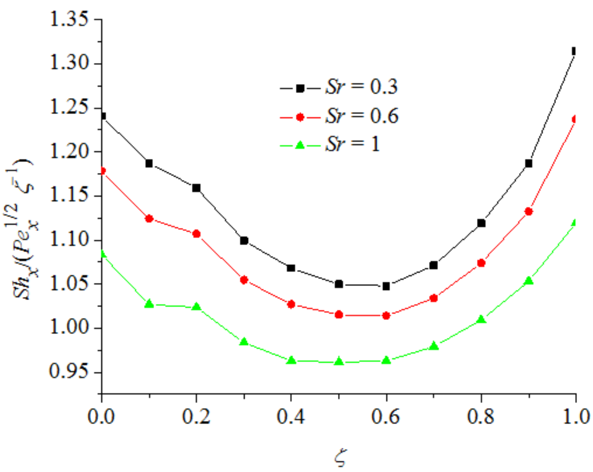

Figure 6: Behavior of Local Sherwood number for distinct amounts of Soret number (S_r)

The effects of Dufour number on the hydrodynamic, temperature, and concentration boundary layer profiles are illustrated in Figures 7-9. It's clear that the rise in the value of Dufour number has the effects of decreasing the velocity and temperature gradients while increasing the concentration gradients slightly. The action of increasing Dufour number on the local Nusselt and Sherwood numbers are exactly opposite to the Soret number as illustrated in Figures 10 and 11, and this effects is more pronounced on the local Nusselt number.

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This is due to the excess in the Dufour number leads to increasing fluid velocity, increasing in concentration gradients, and decreasing in temperature gradients and consequently decreasing the amount of heat transfer and increasing the amount of mass transfer.

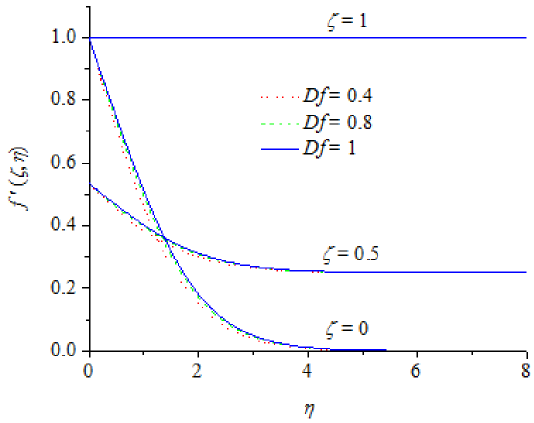

Figure 7: Behavior of fluid velocity for distinct mixed convection parameter (ζ) and Dufour number (D_f) values

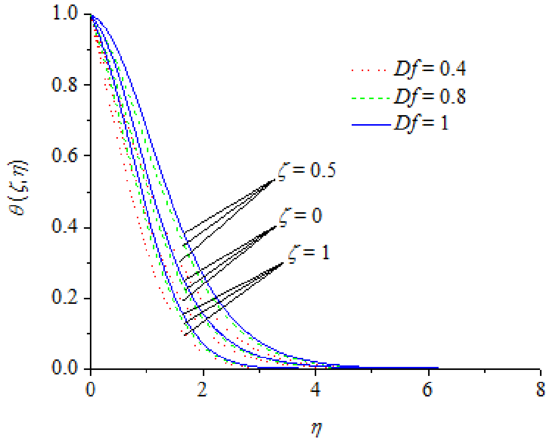

Figure 8: Behavior of fluid temperature for distinct mixed convection parameter (ζ) and Dufour number (D_f) values

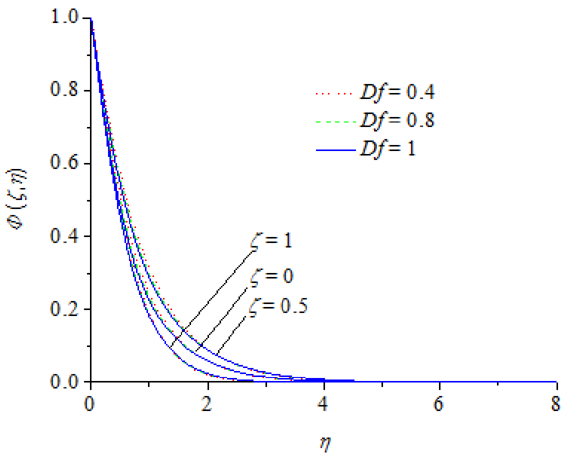

Figure 9: Behavior of fluid concentration for distinct mixed convection parameter (ζ) and Dufour number (D_f) values

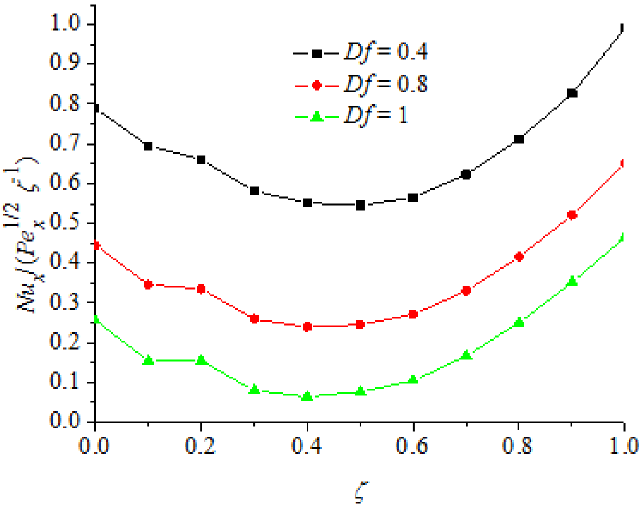

Figure 10: Behavior of Local Nusselt number for distinct amounts of Dufour number (D_f)

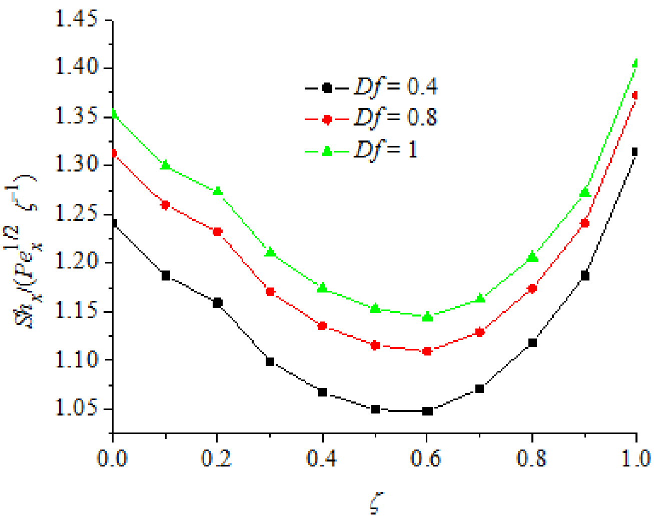

Figure 11: Behavior of Local Sherwood number for distinct amounts of Dufour number (D_f)

Boosting chemical reaction parameter has the effects of increasing the velocity gradients slightly and concentration gradients. Decreasing the temperature gradients slightly as presented in Figures 12-14. It was noticed that the increasing of chemical reaction parameter has similar effects of Dufour number on the local Nusselt and Sherwood numbers but different in amount as depicted in Figures 15 and 16 due to the above reasons. Furthermore, the influences of chemical reaction parameter on the local Sherwood number are greater than from its influences on the local Nusselt number. The physical interpretation to decrease the concentration due to increasing the parameter of chemical reaction is that, the amount of solute molecules subjected to chemical reaction increases as the parameter of chemical reaction increases.

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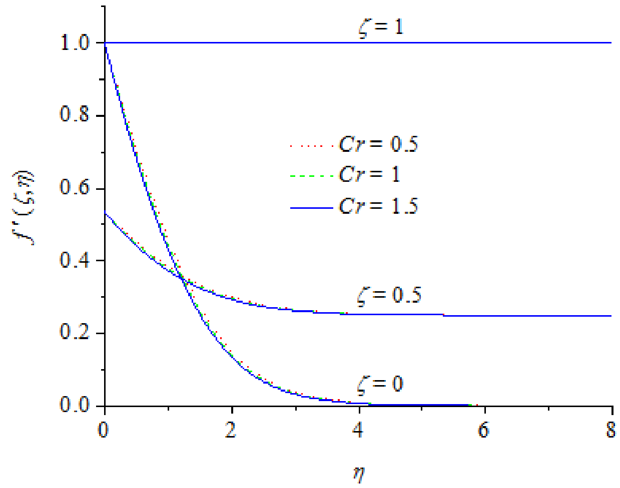

Figure 12: Behavior of fluid velocity for distinct mixed convection parameter (ζ) and chemical reaction parameter (C_r) values

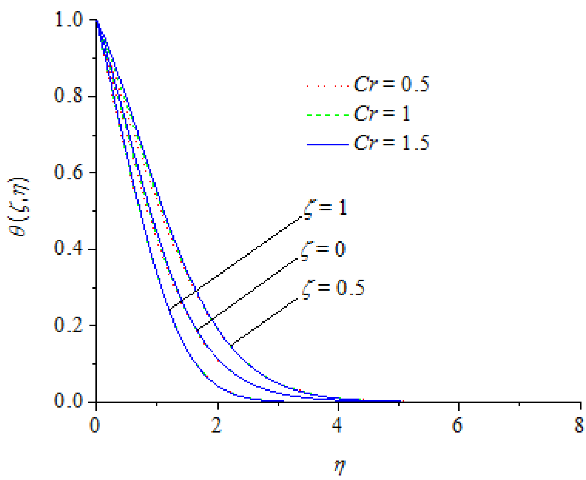

Figure 13: Behavior of fluid temperature for distinct mixed convection parameter (ζ) and chemical reaction parameter (C_r) values

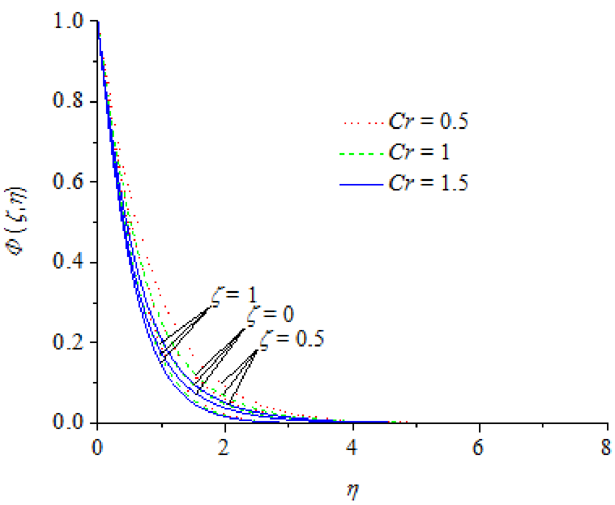

Figure 14: Behavior of fluid concentration for distinct mixed convection parameter (ζ) and chemical reaction parameter (C_r) values

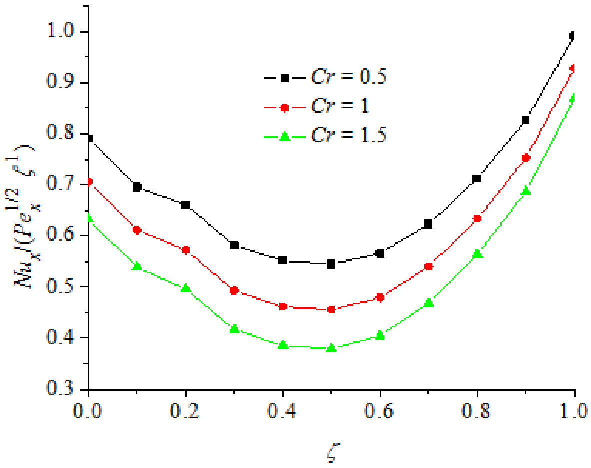

Figure 15: Behavior of Local Nusselt number for distinct amounts of chemical reaction parameter (C_r)

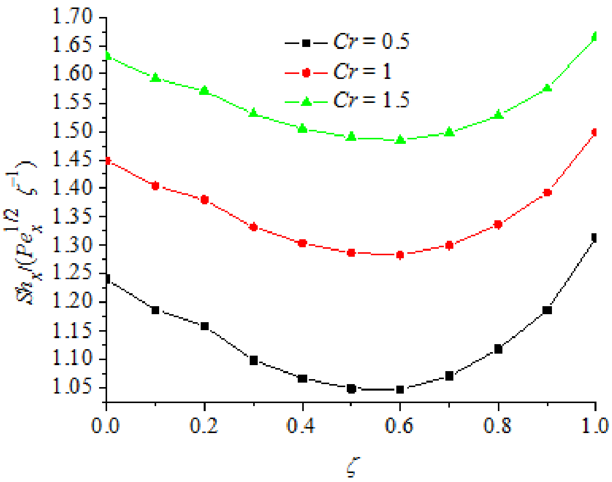

Figure 16: Behavior of Local Sherwood number for distinct amounts of chemical reaction parameter (C_r)

V. CONCLUSION

This work study the effects of Soret and Dufour on the total regime of mixed convection including the natural convection limit and forced convection limit along inverted cone embedded in a non-Darcy porous medium with the chemical reaction. The system of governing nonlinear equations along with the boundary conditions are transformed to dimensionless non-similar form and solved numerically by finite difference method. To evaluate the accuracy of the present numerical results, a comparison for local Nusselt number with previously published work for the case of Darcy solution is conducted and found to be in good agreement.

From the aforementioned results it can be inferred that:

1. Growing the value of the Soret number will enhances the amount of heat transfer and reduce the amount of mass transfer.

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2. Increasing the value of Dufour number has opposite effects of Soret number on the amount of heat and mass fluxes (i.e. decreasing the heat transfer rate and increasing the mass transfer rate).
3. Increasing the value of chemical reaction parameter has similar effects of Dufour number on the amount of heat and mass transfer (i.e. lower heat transfer rate and enhance mass transfer rate).

NOMENCLATURE

A_1, A_2, B	Constants, equation 5
c	Inertia coefficient
c_p	Specific heat $(J.kg^{-1}.K^{-1})$
c_s	Concentration susceptibility
C	Concentration $(kg.m^{-3})$
C_r	Chemical reaction parameter
d	Pore diameter(m)
D	Mass Diffusivity $(m^2.s^{-1})$
D_f	Dufour number
D_s	Thermal dispersion parameter
f	Dimensionless stream function.
g	Gravitational acceleration $(m.s^{-2})$
I	Inertia effect parameter
k_1	Constant of chemical reaction rate of first-order (s^{-1})
k_T	Ratio of thermal diffusion
K	Permeability of the porous medium (m^2)
Le	Lewis number
m	Cone angle parameter
N	Buoyancy ratio
Nu_x	Local Nusselt number
Pe_x	Local Peclet number
$r(x)$	Local radius (m)
Ra_x	Local Rayleigh number
S_r	Soret number
Sh_x	Local Sherwood number
T	Temperature (K)
T_m	Mean fluid temperature (K)
u	Velocity component in the x-direction $(m.s^{-1})$
U	Velocity $(m.s^{-1})$
v	Velocity component in the r-direction $(m.s^{-1})$
x	Axial coordinate (m)
y	Normal coordinate (m)
Greek symbols	
α	Thermal diffusivity $(m^2.s^{-1})$
α_d	Dispersion thermal diffusivity $(m^2.s^{-1})$
β_C	Coefficient of concentration expansion $(m^3.kg^{-1})$
β_T	Coefficient of thermal expansion (K^{-1})
$\Delta\zeta, \Delta\eta$	Subintervals in the ζ and η directions
ζ	Non-similarity parameter
η	Pseudosimilarity variable
ν	Kinematic viscosity of the fluid $(m^2.s^{-1})$
ψ	Stream function
θ	Dimensionless temperature
Φ	Dimensionless concentration
Γ	Coefficient of mechanical dispersion
λ	Constant, equation 5
γ	Cone angle (°)
Subscripts	
max	Sufficiently large value
w	Condition at the cone surface
∞	Free stream conditions

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Citation of this Article:

Saddam Atteyia Mohammad, "Effects of Soret and Dufour on Mixed Convection over a Cone in a Non-Darcy Porous Medium with Chemical Reaction" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 6, Issue 2, pp 86-93, February 2022. Article DOI https://doi.org/10.47001/IRJIET/2022.602015

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