Soret and Dufour effects on chemically reacting mixed convection flow in an annulus with Navier slip and convective boundary conditions

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Abstract

This analysis is to study the incompressible mixed convection laminar Newtonian flow through concentric cylindrical annulus associated with slip and convective boundary conditions. This presentation considered the cross diffusions and chemical reaction effects also. The fluid flow in an annulus is due to the rotation of the outer cylinder with constant velocity. The analysis of such kind of fluid flow is governed by nonlinear partial differential equations. The governing system of equations were mapped into dimensionless system with appropriate transformations. The system has been solved using Homotopy Analysis Method (HAM). The influence of Soret, Dufour, slip parameter and the chemical reaction parameter on velocity, temperature and concentration are investigated, and presented through plots. The maximum values of slip leads to increase in velocity and temperature profiles. Further the impact of boundary conditions on velocity, temperature and concentration are also presented.

Keywords: Mixed Convection, cross diffusion effects, Chemical reaction, convective boundary, Navier slip, HAM.
AMS 2010 codes: 76D05,76E06,65H20,76V05.

1 Introduction

Mixed convection flow with heat and mass transfer in an circular annulus has an incredible significance in various fields. Mixed convection has attracted a great deal of attention from researchers because of its presence both in nature and engineering applications. This type of fluid flow is observed in rotating electrical machines, swirl nozzles, rotating disks, standard commercial rheometers, and other chemical and mechanical mixing equipments. In practical situations, many factors affect the flow and heat transfer through annular space. Considerable research studies were carried out to investigate the Newtonian and non-Newtonian fluid flow through concentric cylinders. The significance and developments of heat and mass transfer have been addressed by many
researchers [1–3]. In view of applications, Modernes et al. [4] presented the numerical study on double-diffusive convection within a tri-dimensional in a horizontal annulus partially filled with a fluid-saturated porous medium. Nagaraju et al. [5] presented the entropy generation analysis of the MHD flow of couple stress fluid between two concentric rotating cylinders with porous lining. Recently, Abedini et al. [6] performed numerical study on mixed convection flow within the horizontal annulus in the presence of water-based fluid with nanoparticles of aluminum oxide, copper, silver and titanium oxide.

Generally, Soret and Dufour effects are assumed negligible in problems related to double diffusive convection. However, such effects could be of significant effect when density differences present in the flow regime. In general, these effects are of a smaller order of magnitude and mostly neglected in heat and mass transfer problems. Especially the thermal-diffusion effect has been utilized for isotope separation and in mixtures between gasses with very light molecular weight \((H_2, He)\) and of medium molecular weight \((N_2, air)\) [7]. Another situation which can arise in practice along with cross diffusions is a chemical reaction produced in the medium. This phenomenon plays an important role in petroleum industry, cooling of nuclear reactors, and packed-bed catalytic reactors [8]. In view of the significance Hayat et al. [9] presented the Soret and Dufour effects in three-dimensional flow over an exponentially stretching surface with porous medium, chemical reaction and heat source/sink. Bilal Ashraf et al. [10] investigated for the effects of Soret and Dufour on the mixed convection flow of an Oldroyd-B fluid with convective boundary conditions. Nagaraju et al. [11] considered the effects of Soret and Dufour, chemical reaction, Hall and ion currents on magnetized micropolar flow through co-rotating cylinders. The analysis of heat and mass transfer in natural convection flow of nanofluid over a vertical cone with chemical reaction is carried out by Reddy and Chamkha [12]. Most recently, Jain and Choudhary [13] investigated the Soret and Dufour effects on thermophoretic MHD flow and heat transfer over a non-linear stretching sheet with chemical reaction.

In this presentation, the mixed convection flow in an annulus with Navier slip condition [14–17] and convective boundary condition [18, 19] were examined in occurrence of Soret and Dufour along with the reaction rate [20–23]. The survey clearly exhibits that cross diffusions and chemical reaction on the slip flow along with convective boundary conditions between concentric cylinders have not been studied elsewhere. In view of significance and applications, the authors are provoked to take this study. Homotopy analysis method (HAM) [24–29] is applied to get solution of system. Series solution of the presented with convergence analysis. The influence of flow parameters on the velocity, temperature and concentration are examined

2 Formation of the problem

Let a steady, incompressible and laminar Newtonian fluid through concentric cylinders has been considered. Radius of inner cylinder is \(a\) and the outer cylinder’s radius is \(b\) \((a < b)\). Choose a cylindrical polar coordinate system \((r, \varphi, z)\) with \(z\) - axis as the common axis of the cylinders (as shown in Fig. 1) and \(r\) normal to the \(z\) - axis. The angular velocity of the outer cylinder is \(\Omega\) whereas the inner cylinder is at rest. The flow is generated due to rotation of the outer cylinder. Rotation of the external cylinder leads to the flow. The parameters depends on \(r\) due to infinitely extended cylinders and the flow is fully developed. The temperature of the fluid is assumed to be \(T_a\). The flow is a mixed convection taking place under thermal buoyancy and uniform pressure gradient in azimuthal direction. The internal and external cylinders are presumed with Navier slip and convective boundary conditions. In addition to the above is considered that the fluid properties are constant except density in the buoyancy term of the balance of momentum equation.

With the above assumptions and Boussinesq approximations with energy and concentration, the equations governing the steady flow of an incompressible fluid [30, 31] are as follows:

\[
\frac{\partial u}{\partial \varphi} = 0
\]
\[ \frac{\partial p}{\partial r} = \frac{\rho u^2}{r} \]  

(2)

\[ \mu \nabla^2 u + \rho g \beta_T (T - T_a) + \rho g \beta_c (C - C_a) - \frac{1}{r} \frac{dp}{d\phi} = 0 \]  

(3)

\[ \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + \frac{\mu}{\rho C_p} \left( \frac{\partial u}{\partial r} - \frac{u}{r} \right)^2 + \frac{DK_T}{C_p} \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) = 0 \]  

(4)

\[ D \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) + \frac{DK_T}{T_m} \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) - K_1 (C - C_a) = 0 \]  

(5)

with

\[ u = \alpha' \left( \frac{\partial}{\partial r} - \frac{u}{r} \right) \right) \frac{\partial}{\partial r} \left( T - T_a \right) + h_{11} (T - T_a) = 0, C = C_a \]  

(6a)

\[ u = b \Omega - \alpha' \left( \frac{\partial}{\partial r} - \frac{u}{r} \right) \right) \frac{\partial}{\partial r} \left( T - T_b \right) + h_{12} (T - T_b) = 0, C = C_b \]  

(6b)

where \( \rho \) is the density, \( p \) is the pressure, \( \mu \) is the viscosity coefficient, \( \alpha' \) is slip length of the internal and external cylinders, \( h_{11}, h_{12} \) are the convective heat transfer coefficients of the internal and external cylinders, \( T_b \) is the ambient temperature. The velocity components in \( r \), \( \varphi \) and \( z \) are \( u, v \) and \( w \) respectively, \( g \) is the acceleration due to gravity, \( K_f \) is the coefficient of thermal conductivity, \( C_p \) is the specific heat, \( \beta_T \) is the coefficient of thermal expansion, \( \beta_c \) is the coefficient of solutal expansion, \( \mu \) is the coefficient of viscosity, \( D \) is the solutal diffusivity, \( T_m \) is the mean fluid temperature and \( K_T \) is the thermal diffusion ratio. \( C_a \) and \( C_b \) are the concentrations at the inner and outer cylinders respectively.

Introducing the following similarity transformations [31]

\[ r = b \sqrt{\lambda}, u = \frac{\Omega}{\sqrt{\lambda}} f(\lambda), T - T_a = \left( T_b - T_a \right) \theta(\lambda), C - C_a = \left( C_b - C_a \right) \phi(\lambda) \]  

(7)

in equations (1) - (5), we obtain the governing dimensionless equations as

\[ 4 \sqrt{\lambda} f'' + \frac{Gr_T}{Re} \theta + \frac{Gr_C}{Re} \phi - A = 0 \]  

(8)

\[ \lambda^3 \theta'' + \lambda^2 \theta' + Br (f - \lambda f)^2 + Df P_r (\lambda^3 \phi'' + \lambda^2 \phi') = 0 \]  

(9)
\[ \lambda f'' + \phi' + ScSr(\lambda \theta'' + \theta') - \frac{K}{4}Sc\phi = 0 \]  

with

\[ -2\alpha \lambda_0 f' (\lambda_0) + (\sqrt{\lambda_0} + 2\alpha) f (\lambda_0) = 0, Bi_1 \theta (\lambda_0) = 2\sqrt{\lambda_0} \theta' (\lambda_0), \phi (\lambda_0) = 0, \text{where} \lambda_0 = \left( \frac{a}{b} \right)^2 \]

\[ 2\alpha f'(1) + (1 - 2\alpha) f(1) = b, Bi_2 (1 - \theta(1)) = 2\theta'(1), \phi(1) = 1 \]  

where the primes represent differentiation with respect to \( \lambda \), \( Re = \frac{\Omega b}{v} \) is the Reynolds number, \( Gr_T = \frac{g\beta_f(T_b - T_a)d^3}{\nu^2} \) is the thermal Grashof number, \( Gr_C = \frac{g\beta_C(C_b - C_a)d^3}{\nu^2} \) is the solutal Grashof number, \( Sc = \frac{\nu}{D} \) is the Schmidt number, \( Pr = \frac{\mu C_P}{K_f} \) is the Prandtl number, \( Br = \frac{\mu \Omega^2}{K_f(T_b - T_a)} \) is the Brinkman number, \( Sr = \)
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Fig. 4 The $h$ curve of $\phi(\lambda)$

Fig. 5 The average residual error of $f(\eta)$

\[ \frac{DK_T(T_b - T_a)}{\nu T_m(C_b - C_a)} \] is the thermo diffusion parameter, \( \alpha = \frac{k}{\rho c_p} \) is the thermal diffusivity, \( A = \frac{d^2}{\mu \Omega r} \) is the constant pressure gradient.

3 Homotopy solution

The initial approximations of the velocity $f(\eta)$, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ [31] are chosen for HAM solutions as:

\[ f_0(\lambda) = \frac{\sqrt{\lambda_0}}{\sqrt{\lambda_0(1 - \lambda_0) + 2\alpha(1 + \lambda_0 \sqrt{\lambda_0})}}, \quad \theta_0(\lambda) = \frac{2\sqrt{\lambda_0} - Bi\lambda_0 + Bi\lambda}{2(\sqrt{\lambda_0} + 1) + Bi(1 - \lambda_0)}, \quad \phi_0(\lambda) = \frac{\lambda - \lambda_0}{1 - \lambda_0}; \] (12)
with the auxiliary linear operator is

\[ L_1 = \frac{\partial^2}{\partial \eta^2} \text{ such that } L_1(c_1 \eta + c_2) = 0 \quad (13) \]

in which \( c_1 \) and \( c_2 \) are the arbitrary constants. \( h_1, h_2 \) and \( h_3 \) (the convergence control parameters) are introduced in zeroth-order deformations.

The zeroth-order deformations; non-linear operators \( N_1, N_2 \) and \( N_3 \); average residual errors of \( f, \theta \) and \( \phi \) are considered as explained in the work of [30].

\[ h \text{-curves are plotted with } Re = 2, Pr = 0.71, Sc = 0.22, Br = 0.5, Gr_T = 4, Gr_C = 4, Sr = 0.1, Df = 0.1, K = 0.1, \alpha = 0.5, Bi = 0.5, b = 1, A = 1 \text{ for the optimal values of } h_1, h_2 \text{ and } h_3 \text{ and are shown in Figs 2-4. The admissible values of } h_1, h_2 \text{ and } h_3 \text{ are noted as -0.35, -0.3, -1.45 respectively with the average residue errors (explained in [30]) shown if Figs. 5-7. Finally the convergence of the series solutions are shown in Table 1.} \]
Table 1 Convergence of HAM solutions for different order of approximations

| Order | \( f(0.625) \) | \( \theta(0.625) \) | \( \phi(0.625) \) |
|-------|----------------|----------------|----------------|
| 1     | 0.5416666667   | 0.3666666667   | 0.5000000000   |
| 5     | 0.5619283426   | 0.5695150828   | 0.6598993682   |
| 10    | 0.5721409664   | 0.621028178    | 0.6609606293   |
| 15    | 0.5721400760   | 0.6528592396   | 0.6609637969   |
| 20    | 0.5721449944   | 0.6528630576   | 0.6609640277   |
| 25    | 0.5721440877   | 0.6528677573   | 0.6609640445   |
| 30    | 0.5721447503   | 0.6528677582   | 0.6609640446   |

Fig. 8 Comparison between exact solution and HAM solution

4 Discussion of Results

Analytic solution for the equation (9) with the boundary conditions (obtained in absence of Brinkman number \( Br \), Dufour parameter \( Df \)) is compared with HAM solution, which are shown in Fig. 8. The comparisons are found to be in a very good agreement. Therefore, the HAM code can be used with great confidence to study the problem considered in this paper.

The profiles of velocity \( f(\lambda) \), temperature \( \theta(\lambda) \) and concentration \( \phi(\lambda) \) are computed and presented through plots in Figs. 9 to 21 with different values of \( Bi, \alpha, Sr, Df, K \). Computations were carried out by fixing the parameters \( Re = 2, Pr = 0.71, Sc = 0.22, Br = 0.5, Gr_T = 5, Gr_C = 5, b = 1, A = 1 \) [31] to analyze the effects of the emerging parameters \( Bi, \alpha, Sr, Df \) and \( K \).

Figures 9-11 shows the impact of Soret number \( Sr \) on \( f, \theta \) and \( \phi \) when \( \alpha = 0.5, Bi=0.5, Df=0.5, K=2 \). It is seen from Fig. 9 that as \( Sr \) increases, the flow velocity decreases by 10%. Soret parameter is the ratio of temperature difference to the concentration. Hence, the higher value of Soret parameter stands for a larger temperature difference and precipitous gradient. Thus the fluid velocity diminishes in circular annulus region due to greater thermal diffusion factor. It is identified from Fig. 10 that the dimensionless temperature diminishes by 23% as \( Sr \) increases. It can depict from Figs. 11 that the dimensionless concentration enhances by 5% with the increase of Soret parameter.

The influence of \( Df \) on \( f, \theta \) and \( \phi \) can be found in Figs. 12 to 14 at \( \alpha = 0.5, Bi=0.5, Sr=0.5, K=0.5 \). It is
noticed from Fig. 12 that the velocity decreases by 7% as $D_f$ magnifies. It is noted from Figs. 13-14 that the temperature of the fluid decreases by 56% and the concentration of the fluid increases by 4% as an increase in $D_f$. This is due to the fact that the Dufour parameter denotes the contribution of the concentration gradients to the thermal energy flux in the flow. Hence the fluid velocity and temperatures are decreases.

Figure 15 presents the influence of chemical reaction parameter on the velocity $f(\eta)$ at $\alpha = 0.5$, $Bi=0.5$, $Sr=0.5$, $D_f=0.5$. It is noted from Fig. 15 that the velocity increases by 5% with an increase in $K$. The impact of chemical reaction parameter on dimensionless temperature can be found in figure. 16. It is seen that the temperature of the fluid increases by 29% with an increase in $K$. Figure 17 depicts the effect of chemical reaction parameter on concentration profile. These results clearly disclose that the flow field is decreased by 3% with the chemical reaction parameter. Higher values of $K$ amount to a fall in the chemical molecular diffusivity, i.e., less diffusion. Therefore, They are obtained by species transfer. An increase in $K$ will suppress species concentration. The concentration distribution decreases at all points of the flow field with the increase in the reaction parameter. This shows that heavier diffusing species have greater retarding effect on the concentration
The effect of slip parameter $\alpha$ on $f$ and $\theta$ can be noted in Figs. 18-19 by fixing the other parameters at $K = 0.5$, $Bi = 0.5$, $Sr = 0.5$, $Df = 0.5$. It is observed that the slip parameter $\alpha$ has significant influence on all the parameters. It is noticed from Fig. 18 that the flow velocity increased by 43% with an increase in $\alpha$. It is found from Fig. 19 that the temperature of the fluid increases by 02% as $\alpha$ increases.

The effect of Biot number $Bi$ on $f$ and $\theta$ can be noted in Figs. 20-21 by fixing the other parameters at $K = 0.5$, $\alpha = 0.5$, $Sr = 0.5$, $Df = 0.5$. Physically, Biot number is expressed as the convection at the surface of the body to the conduction within the surface of the body. Here we have assumed the convective heat transfer coefficients $(h_{11}, h_{12})$ are same at the inner and outer cylinders i.e. $Bi_1 = Bi_2 = Bi$. It depicts from Fig. 20 that the velocity of the fluid increased by 10% as an increase in Biot number. It is due to the fact that Biot number enhances the heat transfer rate in the cylinder walls. It is observed from Fig. 21 that as an increase in Biot number leads to 50% increase in the temperature of the fluid.
5 Conclusion

The present study investigates the steady natural convection flow of Newtonian fluid in an annulus in presence of cross diffusions and chemical reaction effects with Navier slip under convective boundary. Homotopy Analysis Method is used to solve the final dimensionless governing equations. The significant findings are summarized as:

- Fluid flow velocities and temperature profiles decreases where as the concentration profile amplifies with an increase in Sr.
- It is noticed that the presence of Dufour parameter leads to decrease in the velocities and temperature of the fluid but increases the concentration of the fluid.
- The velocity and temperature profiles are increases while concentration of the fluid decreases with the increase in the chemical reaction parameter.
Fig. 15 Chemical reaction effect on \( f(\lambda) \)

Fig. 16 Chemical reaction effect on \( \theta(\lambda) \)

Fig. 17 Chemical reaction effect on \( \phi(\lambda) \)
Fig. 18 Slip parameter $\alpha$ effect on $f(\lambda)$

Fig. 19 Slip parameter $\alpha$ effect on $\theta(\lambda)$

Fig. 20 Effect of Biot number on $f(\lambda)$
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Fig. 21 Effect of Biot number on $\theta(\lambda)$

- The flow velocity and temperature profiles are increases with the increase of slip parameter.
- The presence of Biot number leads increase in velocity and temperature of the fluid.

References

[1] Rogers, B. and Yao, L. S. (1990). The effect of mixed convection instability on heat transfer in a vertical annulus. Int. J. Heat Mass Transfer, 33(1), 79–90.
[2] Tsou, F. K., Win Aung., Moghadam, H. E. and Gau, C. (1992). Wall heating effects in mixed convection in vertical annulus with variable properties. J. Thermophys Heat Transfer, 6(2), 273–276.
[3] Jha, B. K., Daramola, D. and Ajibade, A. O. (2016). Mixed convection in a vertical annulus filled with porous material having time-periodic thermal boundary condition: steady-periodic regime. Meccanica, 51, 1685–1698.
[4] Moderres, M., Abboudi, S., Ihdene, M., Aberkane, S. and Ghezal, A. (2017). Numerical investigation of double-diffusive mixed convection in horizontal annulus partially filled with a porous medium. Int. J. Numer. Methods Heat Fluid Flow, 27(4), 773–794.
[5] Nagaraju, G., Srinivas, J., Murthy, J.V. R. and Rashad, A. (2017). Entropy Generation Analysis of the MHD Flow of Couple Stress Fluid between Two Concentric Rotating Cylinders with Porous Lining. Heat Trans. Asian Res., 46, 316–330.
[6] Abedini, A., Emadoddin, S. and Armaghani, T. (2018). Numerical analysis of mixed convection of different nanofluids in concentric annulus. Int. J. Numer. Methods Heat Fluid Flow, https://doi.org/10.1108/HFF-06-2018-0337.
[7] Jamil, M., Fetecau, C. and Imran, M. (2011). Unsteady helical flows of Oldroyd-B fluids. Commun Nonlinear Sci Numer Simul, 16, 1378–1386.
[8] Nik-Ghazali, N., Badruddin, I. A., Badarudin, A., Badarudin, A. and Tabatabaieikia, S. (2014). Dufour and Soret effects on square porous annulus. Adv. in Mech. Eng, 209753, 1-15.
[9] Hayat, T., Muhammad, T., Shehzad, S.A. and Alsaedi, A. (2015). Soret and Dufour effects in three-dimensional flow over an exponentially stretching surface with porous medium, chemical reaction and heat source/sink. Int. J. Numer. Methods Heat Fluid Flow, 25(4), 762–781.
[10] Bilal Ashraf, M., Hayat, T., Alsaedi, A. and Shehzad, S.A. (2016). Soret and Dufour effects on the mixed convection flow of an Oldroyd-B fluid with convective boundary conditions. Results in Physics, 6, 917–924.
[11] Nagaraju, G., Anjanna, M. and Kaladhar, K. (2017). The effects of Soret and Dufour, chemical reaction, Hall and ion currents on magnetized micropolar flow through co-rotating cylinders. AIP Advances, 7(11), 115201-1–16.
[12] Reddy, P.S. and Chamkha, A. (2017). Heat and mass transfer analysis in natural convection flow of nanofluid over a vertical cone with chemical reaction. Int. J. Numer. Methods Heat Fluid Flow, 27(1), 2–22.
[13] Jain, S. and Choudhary, R. (2018). Soret and Dufour Effects on thermophoretic MHD flow and heat transfer over a non-linear stretching sheet with chemical reaction. Int. J. Appl. Comput. Math, 4(1), 50 (1-27).
[14] Matthews, M.T. and Hill, J.M. (2007). Newtonian flow with nonlinear Navier boundary condition. Acta Mech, 191(3-4), 195–217.
[15] Quarmby, A. (1966). Slip flow in an annulus, Appl. Sci. Res, 16(1), 301–314.
[16] Avci, M. and Aydin, O. (2008). Laminar forced convection slip-flow in a micro-annulus between two concentric cylinders. Int. J. Heat Mass Transfer, 51(13-14), 3460–3467.
[17] Kyritsi-Yiallourou, S. and Georgiou, G. C. (2018). Newtonian Poiseuille flow in ducts of annular-sector cross-sections with Navier slip. Eur. J. Mech. B. Fluids, 72, 87–102.
[18] Malik, R., Khan, M., Munir, A. and Khan, W.A. (2014). Flow and heat transfer in sisko fluid with convective boundary condition. PLoS ONE, 9(10), e107989 (1-11).
[19] Srinivasacharya, D. and Hima Bindu, K. (2016). Entropy generation in a porous annulus due to micropolar fluid flow with slip and convective boundary conditions. Energy, 111, 165–177.
[20] Holman, K. K. and Ashar, S. T. (1971). Mass transfer in concentric rotating cylinders with surface chemical reaction in the presence of Taylor vortexes. Chem. Eng. Sci, 26(11), 1817–1831.
[21] Paul, A. and Deka, R. K. (2013). Chemical reaction effect on transient free convective flow past an infinite moving vertical cylinder. Int. J. Chem. Eng, 531513 (1-9).
[22] Srinivasacharya, D. and Swamy Reddy, G. (2016). Chemical reaction and radiation effects on mixed convection heat and mass transfer over a vertical plate in power-law fluid saturated porous medium. J. Egypt. Math. Soc, 24(1), 108–115.
[23] Anjanna, M. and Nagaraju, G. (2018). Order of chemical reaction and convective boundary condition effects on micropolar fluid flow over a stretching sheet, AIP Advances, 8(11), 115212 (1-10).
[24] Liao, S. J. (2003). Beyond perturbation. Introduction to homotopy analysis method, Chapman and Hall/CRC Press, and Boca Raton.
[25] Liao, S. J. (2004). On the homotopy analysis method for nonlinear problems. Appl Math Comput, 147(2), 499–513.
[26] Rashidi, M.M., Keimanesh, M. and Rajvanshi, S.C. (2012). Study of pulsatile flow in a porous annulus with the homotopy analysis method. Int. J. Numer. Methods Heat Fluid Flow, 22(8), 971–989.
[27] Gibanov, N. S., Shermet, M. A., Oztop, H. F. and Al-Salem, K. (2017). Effect of uniform inclined magnetic field on natural convection and entropy generation in an open cavity having a horizontal porous layer saturated with a ferro fluid. Numer. Heat Transfer, Part A, 72(6), 479–494.
[28] Kaladhar, K. and Komuraiah, E. (2018). Influence of cross diffusions on mixed convection chemical reaction flow in a vertical channel with Navier slip: Homotopy approach. J. Appl. Anal.Comput, 8(1), 379–389.
[29] Nagaraju, G., Srinivas, J., Ramana Murthy, J.V., Bég, O.A. and Kadir, A.A. (2018). Second law analysis of flow in a circular pipe with uniform suction and magnetic field effects. ASME. J. Heat Transfer., 141(1): 012004-1–9.
[30] Srinivasacharya, D. and Kaladhar, K. (2012). Analytical solution of mixed convection flow of couple stress fluid between two circular cylinders with hall and ion-slip effects, Turkish J. Eng. Env. Sci., 36, 226 – 235.
[31] Srinivasacharya, D. and Himabindu, K. (2018). Entropy generation due to micropolar fluid flow between concentric cylinders with slip and convective boundary conditions, Ain Shams Engineering Journal, 9, 245–255.