This paper presents an investigation for bioconvection heat transfer of a nanofluid containing gyrotactic microorganisms over a stretching sheet, in which the effects of radiation, velocity slip and temperature jump are taken into account. The nonlinear governing equations are reduced into four ordinary differential equations by similarity transformations and solved by Homotopy Analysis Method (HAM), which is verified with numerical results in good agree. Results indicate that the density of motile microorganisms and gyrotactic microorganisms increase with bioconvection Rayleigh number, while decrease with increasing in bioconvection Péclet number and bioconvection Lewis number. It is also found that the Nusselt number, Sherwood number and gyrotactic microorganisms density depend strongly on the buoyancy, nanofluids and bioconvection parameters.

Key words: Nanofluid, Gyrotactic microorganisms, Bioconvection, Velocity slip, Temperature jump.

1. Introduction

As a new generation of highly efficient heat transfer fluid, nanofluids have been extensively investigated by many researchers. The term “Nanofluids” was coined by Choi [1] at the ASME Winter Annual Meeting, which refers to a liquid containing a dispersion of submicronic solid particles (nanoparticles) with typical length on the order of 1-50nm. Nanofluids have the higher heat conductivity efficiency than pure fluid due to a volume fraction (usually < 5%) of metal nanoparticles. Heat and mass transfer of nanofluids have been widely investigated.

Nazar et al. [2] studied the unsteady boundary layer flow of a nanofluid over a stretching sheet caused by an impulsive motion or a suddenly stretched surface using the Keller-box method. Buongiorno [3] developed a new correlation explanation for convective heat transport of nanofluids considering the Brownian diffusion. Chamkha and Ismael [4] considered the steady conjugate natural convection heat transfer of three types of nanofluids in a square porous cavity which was heated by a triangular solid wall under a wide range of considered parameter. Xu et al. [5] studied the mixed convection flow of nanofluids caused by both the external pressure and the buoyancy force in a
vertical channel, the effects of the Prandtl number and other parameters were analyzed. In paper [6] the effect of a convective surface on the heat transfer characteristics of nanofluids over a static or moving wedge in the presence of thermal radiation was investigated with three types of nanoparticles considered. Alam and Hossain [7] considered the effects of viscous dissipation and Joule heating on the heat and mass transfer of a two-dimensional steady MHD forced convection flow of nanofluids over a nonlinear stretching sheet and studied numerically.

Recently, Kuznetsov and Nickl [8] analytically studied the natural convective boundary-layer flow of nanofluids past a vertical plate. Unlike the commonly employed constant conditions, a convective heating boundary condition was used in study Makinde and Aziz [9]. Dulal [10] numerically studied the flow and heat transfer of an incompressible viscous fluid past an unsteady stretching permeable sheet. Anbuchezhian et al. [11] studied the flow of nanofluids caused by buoyancy along a vertical plate in a porous medium. Mushtaq et al. [12] investigated radiation effects to two-dimensional stagnation-point flow of viscous nanofluid due to solar energy. Malvandi et al. [13] numerically simulated unsteady stagnation point flow of nanofluids with a slip boundary condition, the results show dual solution would exist when the unsteadiness parameter was negative. The parameters of thermophoresis, Brownian motion and the velocity slip played a vital role in the transport process of various nanofluids. Behseresht et al. [14] displayed that the heat transfer associated with nanoparticles migration was negligible compared with heat conduction and convection on the natural convection heat transfer of nanofluids in a saturated porous medium. Noghrehabadi et al. [15] pointed that the Reynolds number for the temperature profile could be significantly affected by Prandtl number. Rahman et al. [16] numerically investigated the steady boundary layer flow and heat transfer of nanofluids past a permeable exponentially shrinking/stretching surface with second order slip velocity.

Bioconvection is induced by swimming of motile microorganisms, leading the increase of the density of the base fluid. Few studies exist on nanofluids containing gyrotactic microorganisms over a convectively heated stretching sheet. Kuznetsov [17] studied both non-oscillatory and oscillatory nanofluid bio-thermal convection in a horizontal layer of finite depth and analyzed the dependence of the thermal Rayleigh number on the nanoparticle Rayleigh number and the bioconvection Rayleigh number. Khan and Makinde [18] investigated MHD flow of nanofluids with heat and mass transfer along a vertical stretching sheet in the presence of motile gyrotactic microorganisms. Xu and Pop [19] obtained a more physically realistic result using a passively controlled nanofluid model by an analysis of bioconvection flow of nanofluids in a horizontal channel. In a recent paper, Khan et al. [20] investigated the effects of both Navier slip and magnetic field on boundary layer flow of nanofluids containing gyrotactic microorganisms over a vertical plate. Their results show that the bioconvection parameters tend to reduce the local concentration of motile microorganisms. Xu and Pop [21] presented an analysis on the mixed convection flow of a nanofluid over a stretching surface with uniform free stream containing nanoparticles and gyrotactic microorganisms.

In the present paper, we investigate the bioconvection and radiation heat transfer of a nanofluid containing gyrotactic microorganisms over a stretching sheet, in which the effects of Brownian motion and thermophoresis are considered according to Rosseland's approximation [22] as well as velocity slip and temperature jump. We obtain the analytical solutions by using the homotopy
The homotopy analysis method (HAM), as introduced by Liao [23-27], has been adopted to solve the highly nonlinear and coupled differential equations. Many studies have confirmed the effectiveness of this method by contrast.

2. **Mathematical formulation**

We consider in this paper the steady incompressible viscous fluid containing gyrotactic microorganisms near a stagnation-point. In the coordinate system, the origin is a fluid stagnation point and the $x$-axis is the flat direction, that is $y = 0$. The flow region is confined to $y > 0$ and the stretching surface temperature, nanoparticle volume fraction and microorganisms fraction are defined to have constant values $T_w$, $C_w$ and $n_w$ respectively, while at a large value of $y$, temperature, nanoparticle volume fraction and microorganisms fraction have constant values $T_\infty$, $C_\infty$ and $n_\infty$, respectively. Flow induced by bioconvection only take place in a dilute suspension of nanoparticles so that the nanoparticle volume fraction $C$ is lower than 0.01.

The boundary layer governing equations considering thermal radiation and bioconvection are given as follows:

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \mu \frac{\partial^2 u}{\partial y^2} - \mu u / k + (1 - C_w) \rho_f \beta (T - T_w) g / \rho_f - \gamma (\rho_{w_c} - \rho_f) / g / \rho_f$$ (2)

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \tau \left[ D_b / T / \frac{\partial C}{\partial y} / \frac{\partial y}{\partial y} + D_f / T_w \left( \frac{\partial T}{\partial y} \right)^2 \right] - \frac{\partial q_r}{\partial y} / \rho C_p$$ (3)

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_n \frac{\partial^2 C}{\partial y^2} + D_f / T_w \cdot \frac{\partial^2 T}{\partial y^2}$$ (4)

$$u \frac{\partial n}{\partial x} + v \frac{\partial n}{\partial y} = D_n \frac{\partial^2 n}{\partial y^2} - b W_c / (C_w - C_\infty) \cdot \frac{\partial}{\partial y} (n \frac{\partial C}{\partial y}) / \frac{\partial y}$$ (5)

The slip boundary conditions for the governing equations are

$$u = ax + (2 - \sigma_v) \lambda_0 \frac{\partial u}{\partial y} \Bigg|_{y=0}, v = 0,$$

$$T = T_w + \left( 2 - \sigma_T \right) 2 r / (r + 1) \lambda_0 / P r \frac{T}{\partial T / \partial y} \Bigg|_{y=0}, C = C_w, n = n_w, y = 0,$$

$$u = 0, v = 0, T \to T_w, C \to C_w, n \to n_w \text{ when } y \to \infty$$ (6)

where $a$ is a positive constant, $\sigma_v$ and $\sigma_T$ are the tangential momentum accommodation coefficient and the thermal accommodation coefficient [22], $\lambda_0$ is the molecular mean free path and $r$ is the specific heat ratio [28]. $T$ is the temperature, $C$ and $n$ are the densities of nanoparticle and motile microorganisms, $\tau = \left( \rho C_p \right)_f / \left( \rho C_p \right)_p$ is the ratio of effective heat capacity of the nanoparticle material to the heat capacity of the fluid, $\rho_f$ is the density of nanoparticles, $\rho_{w_c}$ is the microorganism density, $\rho_f$ is the base fluid density, $\gamma$ is the average volume of a microorganism, $D_b$ is the Brownian diffusion coefficient, $D_f$ is the thermophoretic diffusion coefficient and $D_n$ is the diffusivity of microorganisms. $\partial q / \partial y = -16 \sigma_q T_w^3 / 3 k T / \partial y^2$ is obtained according to Rosseland’s approximation and the Taylor expansion, $\sigma_q$ and $k$ are.
Stefan–Boltzmann constant and absorption coefficient. Now eq. (3) reduces to
\[
\frac{u\partial T}{\partial x} + \frac{v\partial T}{\partial y} = \left(\alpha + 16\sigma_q T_x^3 / 3\rho c_p k\right) \frac{\partial^2 T}{\partial y^2} + \tau \left[ D_\theta \partial T / \partial y \cdot \partial C / \partial y + D_T / T_c \cdot \left(\partial T / \partial y\right)^2 \right]
\] (7)

The physical flow model and coordinate system is shown in fig. 1.

Figure 1. Flow configuration and coordinate system.

Figure 2. The h-curves of \( f''(0), \theta'(0), \phi'(0) \) and \( \chi'(0) \) of the HAM solution.

3. Similarity transformations

Introducing the stream function and similarity transformation as
\[
\eta = yRa_x^{1/4} / x, \quad \psi = \bar{\alpha} Ra_x^{1/4} f(\eta), \quad \theta(\eta) = (T - T_x) / (T_x - T_w), \quad \phi(\eta) = (C - C_w) / (C_w - C_x),
\]
\[
\chi(\eta) = (n - n_x) / (n_w - n_x), Ra_x = (1 - C_w) \beta g \Delta T_w x^3 / (\rho c_p k),
\]
where \( \bar{\alpha} = \alpha + 16\sigma_q T_x^3 / 3\rho c_p k \), \( \psi \) is the stream function satisfying \( u = \partial \psi / \partial y \) and \( v = -\partial \psi / \partial x \), \( \eta \) is the similarity variable, \( f \) is dimensionless stream function, \( \theta \) is dimensionless temperature function, \( \phi \) and \( \chi \) are dimensionless nanoparticle fraction and microorganisms fraction functions, respectively. eq. (1)–(5) and (7) can be reduced into the following similarity equations:
\[
f''' + 3 / 4 \left(1 / Pr + N\right) f f'' + \theta - N r \phi - R b \chi - A f'' = 0
\] (8)
\[
\theta'' + 3 / 4 f \theta' + N b \theta' \phi' + N t (\theta')^2 = 0
\] (9)
\[
\phi'' + 3 / 4 L e f \phi' + N t / N b \theta'' = 0
\] (10)
\[
\chi'' + 3 / 4 L b f \chi' - P e (\phi' \chi' + \phi'' \chi + \sigma \phi') = 0
\] (11)

and the reduced boundary conditions are:
\[ f'(0) = \lambda_1 + \lambda_2 f''(0), \quad f(0) = 0, \quad \theta(0) = 1 + \delta\theta'(0), \quad \phi(0) = \chi(0) = 1 \] (12)
\[ f' = 0, \quad \theta ightarrow 0, \quad \phi ightarrow 0, \quad \chi ightarrow 0 \text{ as } \eta \rightarrow \infty \] (13)

where \( \lambda_1 = ax^2 Ra_x^{-\frac{1}{2}} / (\alpha + N) \) is the stretching velocity parameter, \( \lambda_2 = \lambda_3 (2 - \sigma_f) Ra_x^{\frac{1}{4}} / \sigma_f \) is the velocity slip parameter, \( \delta = 2r \lambda_3 (2 - \sigma_f) Ra_x^{\frac{1}{4}} / (\sigma_f x Pr (r + 1)) \) is the temperature jump parameter, \( Pr = \mu / \alpha \) is the Prandtl number, \( N = 16 \sigma T_c^3 / 3 \mu \rho c_p k \) is the thermal radiation parameter, \( \Delta C_w = C_w - C_\alpha, \Delta T_w = T_w - T_\alpha, \) \( Rb = \gamma (\rho_\infty - \rho_f) \Delta n_w / \rho_f \beta \Delta T_w (1 - C_\alpha) \) is the bioconvection Rayleigh number \( (\Delta n_w = n_w - n_\alpha) , \quad A = x^2 Ra_x^{\frac{1}{4}} / k \) is the permeability parameter, \( Nb = \tau D_b \Delta C_w Pr / \mu \) and \( Nt = \tau D_t \Delta T_w Pr / T_\alpha \mu \) are the Brownian motion parameter and the thermophoresis parameter, \( Le = \mu / Pr D_b \) is the Lewis number, \( Lb = \mu / Pr D_n \) is the bioconvection Lewis number, \( Pe = bW_c / D_n \) is the bioconvection Péclet number and \( \sigma = n_\infty / \Delta n_w \) is the bioconvection constant.

The reduced local Nusselt number, local Sherwood number and local density number of the motile microorganisms may be found in terms of the dimensionless temperature at the sheet surface, concentration of nanoparticle and microorganisms at the sheet surface, respectively.

\[ Nur = Ra_x^{\frac{1}{4}} Nu_x = -\theta'(0) \] (14)
\[ Shr = Ra_x^{\frac{1}{4}} Sh_x = -\phi'(0) \] (15)
\[ Nnr = Ra_x^{\frac{1}{4}} Nn_x = -\chi'(0) \] (16)

4. HAM solution

The coupled nonlinear boundary value problems eq. (8)-(13) are solved by using the Homotopy analysis method (HAM) [23-27]. The initial approximations are selected as

\[ f_0(\eta) = \lambda_1 (1 - \exp(\eta)) + \lambda_2 (1 + \delta \exp(-\eta)) / (1 + \delta) \] (17)
\[ \phi_0(\eta) = \exp(-\eta), \quad \chi_0(\eta) = \exp(-\eta) \] (18)

The auxiliary linear operators are chosen as follows, respectively

\[ \ell + f'', \quad \ell + \theta', \quad \ell + \phi', \quad \ell + \chi' \] (19)

The nonlinear operators are given by

\[ N_1[f(\eta; q), \theta(\eta; q), \phi(\eta; q), \chi(\eta; q)] = \delta^3 f(\eta; q) / \delta \eta^3 + 3 / 4 (1 / Pr + N) f(\eta; q) \delta^2 f(\eta; q) / \delta \eta^2 + \theta(\eta; q) - N \phi(\eta; q) - Rb \chi(\eta; q) - A \delta f(\eta; q) / \delta \eta \] (20)
\[ N_2[f(\eta; q), \theta(\eta; q), \phi(\eta; q), \chi(\eta; q)] = \delta^2 \theta(\eta; q) / \delta \eta^2 + 3 / 4 f(\eta; q) \delta \theta(\eta; q) / \delta \eta \]
\[ + N b \partial \theta (\eta; q) / \partial \eta - \partial \phi (\eta; q) / \partial \eta + N t (\partial \phi (\eta; q) / \partial \eta)^2 \]  \tag{21} 

\[ N_1 \left[ f (\eta; q), \theta (\eta; q), \phi (\eta; q), \chi (\eta; q) \right] = \partial^2 \phi (\eta; q) / \partial \eta^2 + 3 / 4 Lf (\eta; q) \partial \phi (\eta; q) / \partial \eta + N t / N b \partial^2 \theta (\eta; q) / \partial \eta^2 \]  \tag{22} 

\[ N_4 \left[ f (\eta; q), \theta (\eta; q), \phi (\eta; q), \chi (\eta; q) \right] = \partial^2 \chi (\eta; q) / \partial \eta^2 + 3 / 4 Lbf (\eta; q) \partial \chi (\eta; q) / \partial \eta - P e \partial^2 \phi (\eta; q) / \partial \eta^2 \]  \tag{23} 

with the boundary conditions

\[ \partial^2 f (\eta; q) / \partial \eta^2 \bigg|_{\eta = 0} = \lambda_1 + \lambda_2 \partial^2 f (\eta; q) / \partial \eta^2 \bigg|_{\eta = 0}, f (\eta; q) \bigg|_{\eta = 0} = 0, \theta (\eta; q) \bigg|_{\eta = 0} = 1, \phi (\eta; q) \bigg|_{\eta = 0} = 0, \chi (\eta; q) \bigg|_{\eta = 0} = 1 \]  \tag{24} 

\[ \partial f (\eta; q) / \partial \eta \bigg|_{\eta = \infty} = 0, \theta (\eta; q) \bigg|_{\eta = \infty} = 0, \phi (\eta; q) \bigg|_{\eta = \infty} = 0, \chi (\eta; q) \bigg|_{\eta = \infty} = 0 \]  \tag{25} 

where \( q \in [0, 1] \) is the embedding parameter. The auxiliary functions are chosen as

\[ H_f (\eta) = H_\theta (\eta) = H_\phi (\eta) = H_\chi (\eta) = 1. \]  \tag{26} 

5. Results and discussion

Liao [23-27] pointed out that the auxiliary parameter \( h \) played a vital role in the convergence of the HAM solutions. By means of \( h \)-curves of \( f''(0), \theta'(0), \phi'(0) \) and \( \chi'(0) \)

![Figure 3. Effects of velocity slip parameter \( \lambda_2 \) on velocity.](image1)

![Figure 4. Effects of temperature jump parameter \( \delta \) on temperature.](image2)
in fig. 2 obtained by the 12-th approximation for $Pr = 6$, $Le = 5$, $N = 2$, $\lambda_1 = 1$, $Pe = Nb = Nt = N_f = L_b = \delta = 0.5$, $\lambda_2 = \sigma = 0.2$, $R_b = 0.1$ and $A = 0.01$, it is straightforward to choose a proper value of $h$ to ensure the convergence of the solution series.

Unless special indicated, the values of the parameters in this paper are used as the above values. The reliability of analytical results is verified with numerical solutions obtained by finite difference method using Maple 14.0. The asymptotic boundary conditions at $\eta \to \infty$ were replaced by those at $\eta = 6$.

For illustrations of the results, solutions are plotted for special parameters. In order to validate the present results, a comparison of numerical solutions with the analytical results obtained by HAM is presented in figs. 3–4. The profiles indicate that the two results are in good agreement. The effects of velocity slip $\lambda_2$ on the dimensionless velocity and the profiles of temperature for different values of temperature jump parameter $\delta$ are shown. The velocity value decreases with the velocity slip parameter and the rising in temperature jump parameter leads to the decrease of the surface temperature and thickness of the thermal boundary layer.

![Figure 5. Effects of the stretching velocity parameter $\lambda_1$ on velocity.](image)

![Figure 6. Effects of the thermal radiation parameter $N$ on temperature.](image)

In fig. 5, the effects of stretching velocity parameter $\lambda_1$ on the dimensionless velocity of nanofluids are shown. As the stretching velocity increases, the velocity value decreases. The profiles of temperature distribution for different values of thermal radiation parameter $N$ for $Le = 1$, $Nb = 0.2$ and $N_t = 0.1$ are shown in fig. 6. It indicates that the rising in thermal radiation parameter leads to the increase of the surface temperature and thickness of the thermal boundary layer.

The variation of volume fraction of nanoparticles with transverse distance in the concentration boundary layer is shown in fig. 7 for different values of $Le$. It is found that an increase in Lewis number $Le$ results in reduction of the volume fraction of nanoparticles and concentration boundary layer thickness. This is because Brownian motion coefficient decreases with increasing transverse distance and as a result the rescaled nanoparticle volume fraction decreases rapidly for large Lewis number.
Fig.8 illustrates the effects of the bioconvection Péclet number $Pe$ and the bioconvection constant $\sigma$ on the density of motile microorganisms in nanofluids. It can be seen that the motile microorganism boundary layer thickness decreases with the increasing in $\sigma$ and $Pe$ which is like bioconvection Lewis number $Le$.

The effects of bioconvection Lewis number $Lb$ on the density of motile microorganisms in nanofluids are showed in fig.9. The density of motile microorganisms decreases as $Lb$ increases. Simultaneously, the motile microorganism boundary layer thickness decreases. Like the bioconvection Péclet number, the bioconvection Lewis number plays the same role as regular Lewis number.

The variation of local Nusselt number with different velocity slip parameters and bioconvection Rayleigh numbers for $Nb=Lb=0.1$ is shown in fig.10. It shows that Nusselt number
decreases with an increase in the thermophoresis parameter $N_t$. This is due to that thermophoresis increases the temperature in boundary layer, leading to a rise in the thermal boundary layer thickness.

Fig. 11 displays the variation of the reduced Sherwood numbers for different values of Lewis number, thermophoresis parameter and bioconvection Péclet number for $R_b = \lambda_z = 0.5$ and $N_b = L_b = 0.1$. As expected, the Sherwood number increases with Lewis number while decreases with increasing thermophoresis parameter $N_t$. This is due to the fact that the nanoparticle volume fraction increases with this parameter including the concentration boundary layer, which can be attributed to the fact that when the Lewis number and bioconvection Péclet number are high, the nanoparticle concentration is low. Thus mass transfer from the plate to the fluid since the concentration at the plate surface is higher than that of the fluid.

It can be seen from fig. 12 that the gyrotactic microorganisms density number $N_{nr}$ increases with the bioconvection Péclet number $Pe$, bioconvection constant parameter $\sigma$ and bioconvection Lewis number $L_b$ for $\lambda_z = 0.5$.

![Figure 11. Effects of Le and Nt of Sherwood number.](image1)

![Figure 12. Effects of Pe and \(\sigma\) on density number of the motile microorganisms.](image2)

6. Conclusions

This paper presents an investigation for bioconvection heat transfer of a nanofluid containing gyrotactic microorganisms over a stretching sheet, in which the effects of and radiation, velocity slip and temperature jump are taken into account. The main results can be classified as follows

(a) Velocity profiles decrease with the velocity slip parameter and the stretching velocity parameter.

(b) Temperature decreases with the temperature jump parameter and increases with the thermal radiation parameter inside thermal boundary layer.

(c) Density of nanoparticles decreases with increasing Lewis number inside the boundary layer.
(d) Density of motile microorganisms decreases with increasing bioconvection Péclat number, bioconvection constant and bioconvection Lewis number inside the boundary layer.

(e) Nusselt number decreases with an increase in slip parameter, bioconvection Rayleigh number and thermophoresis parameter. Sherwood number increases with Lewis number, whereas decreases with thermophoresis parameter. The gyrotactic microorganisms density number increases with bioconvection Péclat number, bioconvection constant parameter and bioconvection Lewis number.

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Nomenclature

\[ a \] - a positive constant, \([\text{s}^{-1}]\)
\[ A \] - permeability parameter, [-]
\[ C \] - nanoparticle fraction, [-]
\[ g \] - gravitational field, \([\text{m/s}^2]\)
\[ k \] - absorption coefficient, [-]
\[ n \] - microorganisms fraction, [-]
\[ Ra_\lambda \] - local Rayleigh number, [-]
\[ T \] - temperature, \([\text{K}]\)
\[ u, v \] - fluid velocity component in x-direction and y-direction, \([\text{m/s}]\)
\[ x, y \] - streamwise coordinate and cross-stream coordinate, \([\text{m}]\)

Greek letters

\[ \mu \] - dynamic viscosity, \([\text{Pa s}]\)
\[ \rho \] - density, \([\text{kg/m}^3]\)
\[ \beta \] - volumetric expansion coefficient, [-]
\[ \alpha \] - the effective thermal diffusivity, \([\text{m}^2\text{s}^{-1}]\)
\[ \gamma \] - average volume of a microorganism, \([\text{m}^3]\)
\[ \sigma_v \] - tangential momentum accommodation coefficient, [-]
\[ \sigma_T \] - thermal accommodation coefficient, [-]
\[ \sigma_s \] - Stefan–Boltzmann constant, [-]
\[ \eta \] - similarity variable, [-]
\[ \rho C_p \] - heat capacity, \([\text{JK}^{-1}\text{m}^{-3}]\)
\[ \lambda_1 \] - stretching velocity parameter, [-]
\[ \lambda_2 \] - velocity slip parameter, [-]
\[ \delta \] - temperature jump parameter, [-]

Subscripts

\[ w \] - the surface
\[ \infty \] - large value of \( y \)
\[ f \] - nanofluid
\[ p \] - nanoparticle

References


