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EFFECTS OF THERMOPHORESIS AND VARIABLE PROPERTIES ON FREE CONVECTION ALONG A VERTICAL WAVY SURFACE IN A FLUID SATURATED POROUS MEDIUM

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ABSTRACT

An analysis is presented for the steady natural convection heat and mass transfer over a vertical wavy surface in a homogeneous Darcy porous medium with thermophoresis and variable properties included. The governing boundary layer equations for momentum, energy and concentration are transformed into a system of ordinary differential equations by using an appropriate transformation and then solved by employing the Runge-Kutta method with shooting technique. A parametric study illustrating the influence of variable viscosity, variable thermal conductivity and thermophoresis parameter on the fluid velocity, temperature and concentration profiles as well as rate of heat and mass transfer is conducted. The computations in the absence of variable properties and themophoresis effects correlate accurately with the earlier published results. Increasing thermophoresis parameter strongly enhances the velocity and concentration profiles and Nusselt number where as depreciation in temperature profile and Sherwood number. The study has applications in aerosol Technology, space technology and processes involving high temperatures.

Keywords: *Variable Properties; Heat and Mass Transfer in Porous Media; Vertical Wavy Surface; Thermophoresis.*

INTRODUCTION

Double diffusive convection heat and mass transfer in a fluid saturated Darcy porous medium are considerable interest in many geophysical, geothermal and industrial applications such as dispersion of chemical contaminants through water saturated soil, grain storage installations, in the design of pebble bed nuclear reactors, compact heat exchangers, oil extraction, petroleum reservoirs and heat transfer from storage of agricultural products which generate heat as a result of metabolism. Surfaces with intentionally roughness elements are considered to enhance heat transfer. The roughness elements disturb the flow pass and alter the rate of heat transfer. Natural convection from irregular (example wavy) surfaces can be used for transferring heat in several heat transfer devices, such flat plate condensers in refrigerators and solar collectors. Recently, Hady *et.al* [1] investigated MHD free convection flow along a vertical wavy surface with heat generation or absorption effect. Shalini and Rathish Kumar [2] studied the influence of variable heat flux on natural convection along a corrugated wall in porous media. Mohamed *et.al* [3] employed an efficient numerical technique based on the Shooting method to analyze combined radiation and free convection from a vertical wavy surface embedded in porous media. Nasser and Nader [4] conducted a numerical study of the effects of variable properties on MHD unsteady natural convection heat and mass transfer over a vertical wavy surface. Rathish kumar and Krishna Murthy [5] studied Soret and Dufour effects on double diffusive free convection from a corrugated vertical surface in a non-Darcy porous medium. Maria [6] studied free convection heat and mass transfer induced by a constant heat and mass fluxes vertical wavy wall in a non-Darcy double stratified porous medium. Narayana *et.al* [7] used an implicit finite difference method with Keller box scheme to analyze double diffusive convection and cross diffusion effects on a horizontal wavy surface in a porous medium. Siddiqa and Anwar Hossain [8] presented numerical results of natural convection flow over wavy horizontal surface.

Thermophoresis is a phenomenon, which causes the migration of aerosol and other particles in the direction of a decreasing temperature gradient. Thermophoresis plays an important role in the engineering analysis community owing to major applications in optical fiber production, aerosol reactors, heat exchanger fouling etc. This phenomenon has many practical applications in removing small particles from gas particle trajectories from combustion devices, particles impacting the blade surface of gas turbines, particle surfaces produced by condensing vapor gas mixtures, and ohters such as filtration in gas - cleaning and nuclear reactor safety. Adrian [9] considered the effect of thermophoresis particle deposition in free convection boundary layer from a horizontal flat plate embedded in a porous medium.

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Rashad [10] studied the effect of radiation on MHD free convection from a vertical flat plate embedded in porous media with thermophoretic deposition of particles. Seddeek *et.al* [11] conducted numerical study for the effects of thermophoresis and variable thermal conductivity on heat and mass transfer over an accelerating surface with heat source. Tsai and Huang [12] developed thermophoresis and electrophoresis on particle deposition onto a vertical flat plate from mixed convection flow through a porous medium. Bakier and Subba Reddy [13] proposed the combined effects of thermophoresis and radiation on laminar flow along a semi - infinite vertical plate. Das [14] discussed the influence of thermophoresis and chemical reaction on MHD micropolar fluid flow with variable fluid properties. Ganesan *et.al* [15] investigated thermophoresis particle deposition effects in a free convective doubly stratified medium over a vertical plate.

Most of the previous studies about vertical wavy surfaces are mainly concerned with free convection in the presence of variable properties. Thermophoresis effect on double diffusive convective heat and mass transfer by free convection in a fluid saturated porous medium has not been studied so far. The non-linear, coupled momentum, energy and concentration equations are transformed into non-dimensional form by using similarity transformations and then solved by using the numerical method, Runge-Kutta method. The results are reported for various physical parameters, variable viscosity, variable thermal conductivity and thermophoresis parameter on flow velocity, temperature and concentration distributions as well as rate of heat and mass transfer graphically.

FORMULATION OF THE PROBLEM

We consider laminar, steady, viscous, incompressible two-dimensional flow of fluid on natural convective heat and mass transfer past a vertical wavy plate embedded in a Darcy saturated porous medium. The configuration of the problem is shown in Fig. 1. The wavy configuration is defined as

$$\bar{\sigma}(\bar{x}) = \bar{a} sin\left(\frac{\pi \bar{x}}{l}\right)$$

where l and $\bar{a}$ are characteristic length and the amplitude of the wavy surface respectively. The wavy plate is considered along x-axis, which is maintained at constant temperature T_w and constant concentration T_∞ and y-axis is assumed to be normal to the wavy plate. In view of the above assumptions and Boussinesq approximation the governing boundary layer equations for flow momentum, energy and concentration are:

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

$$\frac{\partial}{\partial \bar{y}}\left(\frac{\mu}{K}\bar{u}\right) = \frac{\partial}{\partial \bar{x}}\left(\frac{\mu}{K}\bar{v}\right) + \rho g\left(\beta_t \frac{\partial T}{\partial \bar{y}} + \beta_c \frac{\partial C}{\partial \bar{y}}\right) \tag{2}$$

$$\bar{u}\frac{\partial T}{\partial \bar{x}} + \bar{v}\frac{\partial T}{\partial \bar{y}} = \frac{\partial}{\partial \bar{x}}\left(\alpha \frac{\partial T}{\partial \bar{x}}\right) + \frac{\partial}{\partial \bar{y}}\left(\alpha \frac{\partial T}{\partial \bar{y}}\right) \tag{3}$$

$$\bar{u}\frac{\partial C}{\partial \bar{x}} + \bar{v}\frac{\partial C}{\partial \bar{y}} = D\left(\frac{\partial^2 C}{\partial \bar{x}^2} + \frac{\partial^2 C}{\partial \bar{y}^2}\right) - \frac{\partial}{\partial \bar{x}}\left(U_T C\right) - \frac{\partial}{\partial \bar{y}}\left(V_T C\right) \tag{4}$$

The corresponding boundary conditions are

$$\left.\begin{array}{l} \bar{u} = 0; \bar{v} = 0; T = T_w; C = C_w \quad \text{at} \quad \bar{y} = \bar{\sigma}(\bar{x}) = \bar{a}\ sin\left(\frac{\pi \bar{x}}{l}\right) \\ \bar{u} \to 0; T \to T_\infty; C \to C_\infty \quad \text{as} \quad \bar{y} \to \infty \end{array}\right\} \tag{5}$$

where $\bar{u}$ and $\bar{v}$ are the volume averaged velocity components in $\bar{x}$ and $\bar{y}$ directions, respectively. Properties μ is the variable viscosity, ρ is the fluid density and K is the permeability of the porous medium, β_t is the coefficients of thermal expansion, β_c is the coefficient of concentration expansion, D is the mass diffusivity of the saturated porous medium and g is the acceleration due to gravity. The fluid properties are assumed to be isotropic and constant except the fluid viscosity and fluid thermal conductivity. The fluid viscosity is assumed to be vary as an inverse linear function of the temperature (see Lai and Kulacki [16]) as

$$\frac{1}{\mu} = \frac{1}{\mu_\infty}\left(1 + \delta(T - T_\infty)\right) \text{ or } \frac{1}{\mu} = b(T - T_r) \tag{6}$$

where $b = \frac{\delta}{\mu_\infty}$ and $T_r = T_\infty - \frac{1}{\delta}$. Both b and T_r are constants and their values depend on the reference state and the thermal property of the fluid i.e. $\delta.\theta_r$, which is defined by $\theta_r = \frac{T_r - T_\infty}{T_w - T_\infty} = -\frac{1}{\delta(T_w - T_\infty)}$ is constant. It is an important to note that for δ→0 (i.e. $\mu=\mu_\infty$=constant) then $\theta_r \to \infty$. It is also mentioning here that b>0 for liquids and b<0 for gases. Thus, θ_r is positive for gases and negative for liquids. T_∞ is the free stream temperature. Also, we assume that the fluid thermal conductivity α is assumed to vary as a linear function of temperature in the form (see Seddeek and Salem [17]):

$$\alpha = \alpha_o \left(1 + E(T - T_\infty)\right)$$

where α_0 is the thermal diffusivity at the wavy surface temperature T_w and E is a constant depending on the nature of the fluid. It is worth mentioning here that E<0 for fluids such as lubrication oils, while E>0 for fluids such as air, water.

This can be written in the non-dimensional form (see Slattery [18]) as

$$\alpha = \alpha_o \left(1 + \beta\theta\right) \tag{7}$$

where $\beta = E(T_w - T_\infty)$ is the thermal conductivity parameter and T_w is the wavy surface temperature.

In Eq. [4] U_T and V_T are thermophoretic velocities which can be written as (see Wu and Greif [19])

$$U_T = -\frac{k\nu}{T_r}\frac{\partial T}{\partial \bar{x}} \text{ and } V_T = -\frac{k\nu}{T_r}\frac{\partial T}{\partial \bar{y}} \tag{8}$$

where k is thermophoretic coefficient which ranges in the values between 0.2 and 1.2 and is defined as (see Talbot *et.al* [20])

$$k = \frac{2C_s\left(\lambda_g / \lambda_p + C_t Kn\right)\left[1 + Kn\left(C_1 + C_2 e^{-C_3/Kn}\right)\right]}{\left(1 + 3C_m Kn\right)\left(1 + 2\lambda_g / \lambda_p + 2C_t Kn\right)}$$

where C_1, C_2, C_3, C_m, C_s, C_t are constants, λ_g and λ_p are thermal conductivities of fluid and diffused particles, respectively and Kn is the Knudsen number.

We define the stream function $\bar{\psi}$, which is to be satisfied the continuity equation (1) such that

$$\bar{u} = \frac{\partial \bar{\psi}}{\partial \bar{y}}, \bar{v} = -\frac{\partial \bar{\psi}}{\partial \bar{x}}$$

In order to write the governing boundary layer equations in non-dimensional form, we introduce the following dimensionless variables

$$\left.\begin{aligned} &x = \bar{x}/l, \quad y = \bar{y}/l, \quad a = \bar{a}/l, \quad \sigma = \bar{\sigma}/l \\ &\psi^* = \bar{\psi}/\alpha_o, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi = \frac{C - C_\infty}{C_w - C_\infty} \end{aligned}\right\} \tag{9}$$

Using Eqs. (6)- (9), Eqs. (2)-(4) becomes

$$\frac{1}{\theta - \theta_r}\left(\frac{\partial\theta}{\partial y}\frac{\partial\psi^*}{\partial y} + \frac{\partial\theta}{\partial x}\frac{\partial\psi^*}{\partial x}\right) + \frac{\partial^2\psi^*}{\partial y^2} + \frac{\partial^2\psi^*}{\partial x} = Ra\left(1 - \frac{\theta}{\theta_r}\right)\left(\frac{\partial\theta}{\partial y} + N\frac{\partial\phi}{\partial y}\right) \tag{10}$$

$$\frac{\partial\psi^*}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial\psi^*}{\partial x}\frac{\partial\theta}{\partial y} = \beta\left(\left(\frac{\partial\theta}{\partial x}\right)^2 + \left(\frac{\partial\theta}{\partial y}\right)^2\right) + (1 + \beta\theta)\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2}\right) \tag{11}$$

$$Le\left(\frac{\partial\psi^*}{\partial y}\frac{\partial\phi}{\partial x}-\frac{\partial\psi^*}{\partial x}\frac{\partial\phi}{\partial y}\right)=\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}-Sc\tau\left(\frac{\partial^2\theta}{\partial x^2}\phi+\frac{\partial^2\theta}{\partial y^2}\phi+\frac{\partial\theta}{\partial x}\frac{\partial\phi}{\partial x}+\frac{\partial\theta}{\partial y}\frac{\partial\phi}{\partial y}\right) \tag{12}$$

where $Ra=\dfrac{g\beta_t K(T_w-T_\infty)l}{\alpha_o\nu}$ is the Darcy-Rayleigh number,

$\nu=\dfrac{\mu_\infty}{\rho}$ is the kinematic viscosity of the fluid,

$N=\dfrac{\beta_c(C_w-C_\infty)}{\beta_t(T_w-T_\infty)}$ is the buoyancy ratio,

$Le=\dfrac{\alpha_o}{D}$ is the Lewis number,

$\tau=-\dfrac{k}{T_r}(T_w-T_\infty)$ is the Thermophoretic parameter,

and $Sc=\dfrac{\nu}{D}$ is the Schmidt number.

The associated boundary conditions are given by

$$\left.\begin{array}{lll}\psi^*=0, \quad \theta=1, \quad \phi=1 & \text{on} & y=a\,sin(x),\\ \psi^*_y\to 0, \quad \theta\to 0, \quad \phi\to 0 & \text{as} & y\to\infty.\end{array}\right\} \tag{13}$$

Let us consider the following transformations

$$x=\xi, \quad \eta=\frac{y-asin(x)}{\xi^{1/2}Ra^{-1/2}}, \quad \psi^*=Ra^{1/2}\psi. \tag{14}$$

Substituting Eq. (14) into Eqs.(10)-(13) and letting Ra→∞, to transfer the effect of the wavy surface from the boundary conditions into governing equations, we obtain the following boundary layer equations:

$$\frac{1}{\theta-\theta_r}\left(1+a^2cos^2\xi\right)\frac{\partial\theta}{\partial\eta}\frac{\partial\psi}{\partial\eta}+\left(1+a^2cos^2\xi\right)\frac{\partial^2\psi}{\partial\eta^2}=\xi^{1/2}\left(1-\frac{\theta}{\theta_r}\right)\left(\frac{\partial\theta}{\partial\eta}+N\frac{\partial\psi}{\partial\eta}\right) \tag{15}$$

$$\beta\left(1+a^2cos^2\xi\right)\left(\frac{\partial\theta}{\partial\eta}\right)^2+\left(1+\beta\theta\right)\left(1+a^2cos^2\xi\right)\frac{\partial^2\theta}{\partial\eta^2}=\xi^{1/2}\left(\frac{\partial\psi}{\partial\eta}\frac{\partial\theta}{\partial\xi}-\frac{\partial\psi}{\partial\xi}\frac{\partial\theta}{\partial\eta}\right) \tag{16}$$

$$\begin{aligned}\left(1+a^2cos^2\xi\right)\frac{\partial^2\phi}{\partial\eta^2}-Sc\tau\left(\left(1+a^2cos^2\xi\right)\phi\frac{\partial^2\theta}{\partial\eta^2}+\left(1+a^2cos^2\xi\right)\frac{\partial\theta}{\partial\eta}\frac{\partial\phi}{\partial\eta}\right)\\ =Le\xi^{1/2}\left(\frac{\partial\psi}{\partial\eta}\frac{\partial\phi}{\partial\xi}-\frac{\partial\psi}{\partial\xi}\frac{\partial\phi}{\partial\eta}\right)\end{aligned} \tag{17}$$

In order to transform Eqs. (15) - (17) into a set of ordinary differential equations, we introduce the following similarity transformations

$$\hat{\eta}=\frac{\eta}{1+a^2cos^2\xi}, \quad \psi=\xi^{1/2}f(\hat{\eta}), \quad \theta=\theta(\hat{\eta}) \text{ and } \phi=\phi(\hat{\eta}) \tag{18}$$

Thus, we obtain

$$f''+\frac{1}{\theta-\theta_r}\theta' f'=\left(1-\frac{\theta}{\theta_r}\right)\left(\theta'+N\phi'\right) \tag{19}$$

$$\beta(\theta')^2+(1+\beta\theta)\theta''+\frac{1}{2}f\theta'=0 \tag{20}$$

$$\phi'' + \left(\frac{1}{2}Lef - Sc\tau\theta'\right)\phi' - Sc\tau\phi\theta'' = 0 \tag{21}$$

where prime denotes differentiation with respect to $\hat{\eta}$.

The associated boundary conditions are

$$\left.\begin{array}{l} f = 0, \quad \theta = 1, \quad \text{and} \quad \phi = 1 \quad \text{at} \quad \hat{\eta} = 0 \\ f' \to 0, \quad \theta \to 0 \quad \text{and} \quad \phi \to 0 \quad \text{as} \quad \hat{\eta} \to \infty \end{array}\right\} \tag{22}$$

The engineering design quantities of physical interest include Nusselt number and Sherwood numbers which are defined as

$$Nu_\xi = \frac{-\theta'(0)Ra_\xi^{1/2}}{(1+a^2cos^2(\xi))^{1/2}} \quad and \quad Sh_\xi = \frac{-\phi'(0)Ra_\xi^{1/2}}{(1+a^2cos^2(\xi))^{1/2}} \tag{23}$$

RESULTS AND DISCUSSIONS

The transformed boundary layer equations given by (19) - (21) subjected to appropriate boundary conditions (22) are solved by using Runge-Kutta method with shooting technique. To validate the present method the results are compared with previously published results. Table-1 shows the comparison results in the absence of variable properties for vertical flat plate (i.e., a=0) and thermophoresis with Cheng [21]. The results are found to be good agreement. The results by the aforesaid method are expressed in terms of flow velocity, temperature and concentration profiles as well as rate of heat mass transfer, and all the results then explained through graphically as shown in Figs. (2) - (18)

Table-1: Comparison of the rate of heat and mass transfer for a=0, β=0, τ=0 and $\theta_r \to \infty$ at N=1, and Le=0.5.

Parameters		$Nu_x Ra_x^{-1/2}$	$Sh_x Ra_x^{-1/2}$	$Nu_x Ra_x^{-1/2}$	$Sh_x Ra_x^{-1/2}$
Le	**N**	**Cheng [21]**	**Cheng [21]**	**Present**	**Present**
1	4	0.992	0.992	0.9923	0.9923
10	4	0.681	3.290	0.6809	3.2883
100	4	0.521	10.521	0.5208	10.5205
4	1	0.559	1.358	0.5558	1.3565
4	2	0.650	1.624	0.6510	1.6238
4	3	0.728	1.852	0.7275	1.8532

Fig. (2) represents the variation of variable viscosity θ_r on velocity profile. It is observed that increasing in θ_r results depreciation at the beginning until it reaches a particular value, then increases until the value becomes constant, that is zero, at the outside the boundary layer. Fig. (3) shows the results of variable viscosity (θ_r) on temperature (θ) profile. It is noted that temperature profile increases with increase in θ_r. From fig. (4) it is clear that concentration profile increased with increase in θ_r. Thus, increase in θ_r leads to enhance thermal and solutal boundary layer thickness.

Figs. (5) - (7) represents the variation of variable thermal conductivity β on flow velocity, temperature and concentration distributions respectively. From fig. (5) it is noted that the velocity profile has similar behaviour as in fig. (2). However the change in velocity is larger as shown in fig. (5) with increase in β. We assumed that variable thermal conductivity (β) is to vary as a linear function of the temperature. It means that temperature profile significantly increased with increase in β as shown in fig. (6). But the opposite results are noted for concentration profile as mentioned in fig. (7) with increase in β.

The variation of thermophoresis parameter (τ) on flow velocity, temperature and concentration distributions has been displayed in figs. (8) - (10). From fig. (8) it is observed that increasing thermophoresis parameter(τ) tends to increase significantly i.e., increase the thickness of the velocity boundary layer. Fig. (9) reveals that the temperature profile decreased considerably with increase in τ. From fig. (10) it is seen that increase in thermophoresis parameter leads to rise the results of concentration profile. In other words increase in τ decelerates the thermal boundary layer thickness while accelerate the solutal boundary layer thickness.

The influence of variable viscosity (θ_r) parameter on the rate of heat (Nusselt number) and mass (Sherwood number) transfer with stream wise coordinate ξ is exhibited in Figs. (11) - (12). It is observed that as θ_r increases, both Nusselt number and Sherwood number decreases. The influence of variable thermal conductivity (β) on Nusselt number and Sherwood number with stream wise coordinate is highlighted in figs. (13) and (14) respectively. From these figures it is seen that increase in β tends to decrease in Nusselt number but conversely enhance Sherwood number. The variation of thermophoresis parameter (τ) on Nusselt number and Sherwood number is depicted in figs. (15) and (16). It is observed that as τ increase, rate of heat transfer increases but rate of mass transfer is reduced with increase in τ. The variation of the amplitude of the wavy surface (a) on Nusselt number and Sherwood number are illustrated in (17) and (18). These results shows that with increase in a, Nusselt number and Sherwood number decreases and hence the amplitude of the Nusselt number and Sherwood decreased for large values of a. It is an important to note that for a=0 the vertical wavy surface becomes flat surface.

CONCLUSTIONS

The thermophoresis effect on the free convection heat and mass transfer along a vertical wavy surface embedded in a fluid saturated porous medium is analyzed numerically. Conservation equations for mass, momentum, energy and concentration are transformed into non-dimensional boundary layer equations by using a simple coordinate transformation and then solved by using Runge-Kutta method with Shooting technique. The results for various physical parameters are reported graphically. The following conclusions can be made:

- Increase in variable viscosity results depreciation in velocity profile, Nusselt number and Sherwood number while there is an enhancement in temperature and concentration profiles.
- Velocity and temperature profiles and Sherwood number are increased for large values of variable thermal conductivity parameter, but the opposite results are reported for concentration profile and Nusselt number.
- Increase in thermophoresis parameter leads to enhance the flow velocity and concentration and Nusselt number while depreciation in temperature profile and Sherwood number.
- Increasing the amplitude of the wavy surface decelerates the amplitude of the Nusselt number and Sherwood number.

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GRAPHS

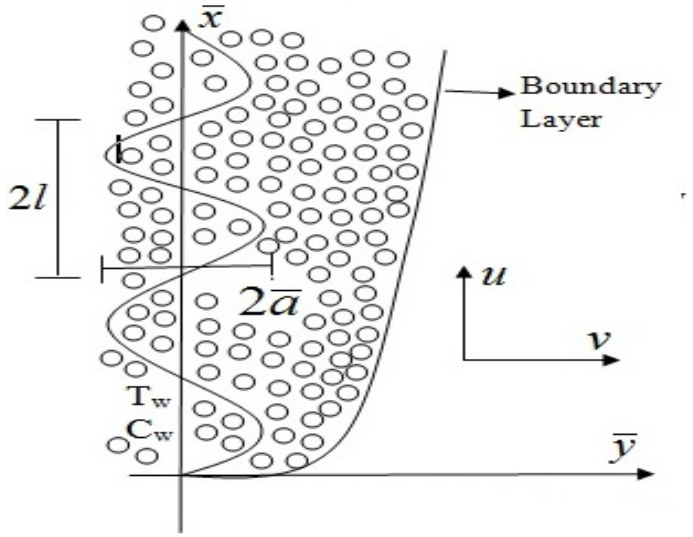

Fig-1: Physical configuration of the Problem

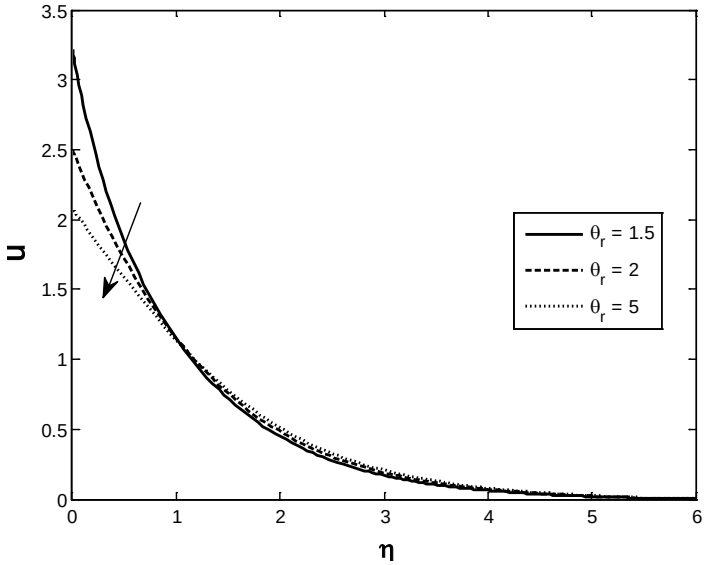

Fig-2: Velocity profile for different values of θ_r for N = 1, Le = 0.5, β = 0.5, Sc = 0.6 and τ= 1

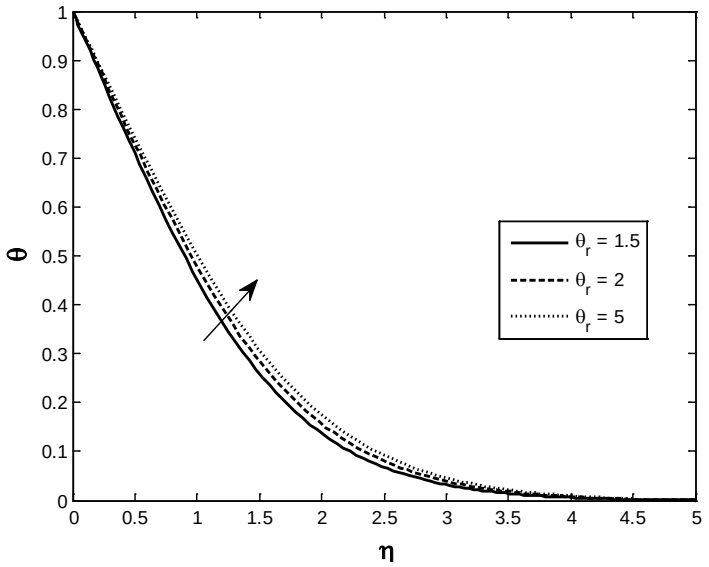

Fig-3: Temperature profile for different values of θ_r for N = 1, Le = 0.5, β = 0.5, Sc = 0.6 and τ= 1

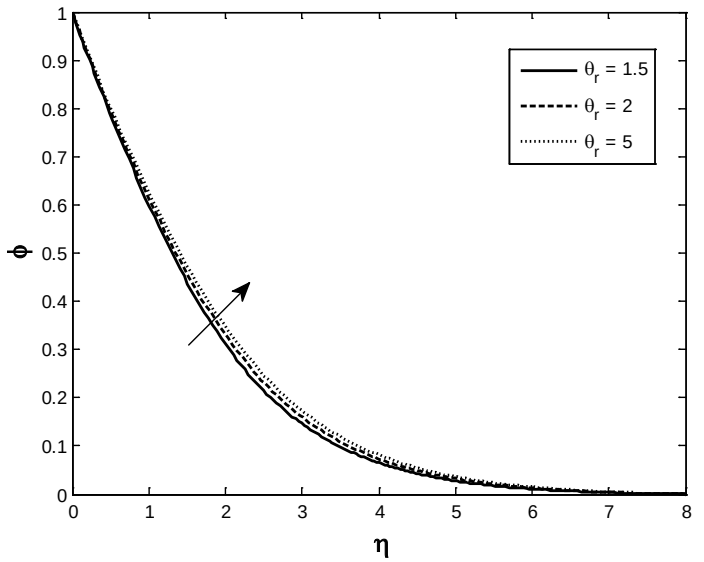

Fig-4: Concentration profile for different values of θ_r for N = 1, Le = 0.5, β = 0.5, Sc = 0.6 and τ= 1

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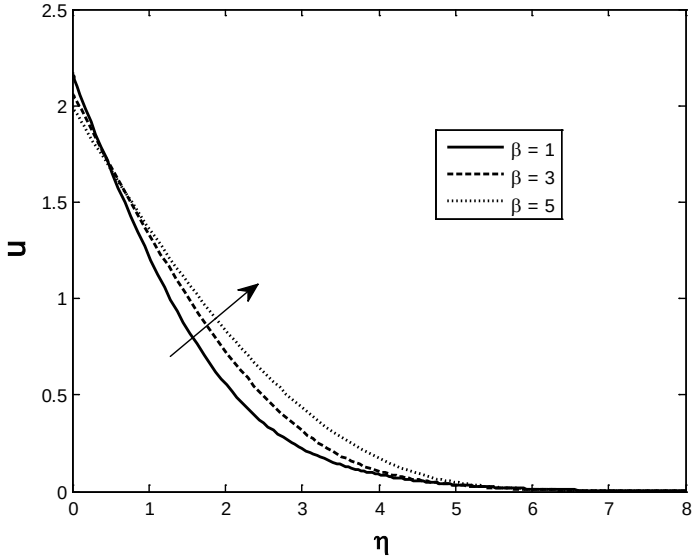

Fig-5: Velocity profile for different values of β for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and τ= 1

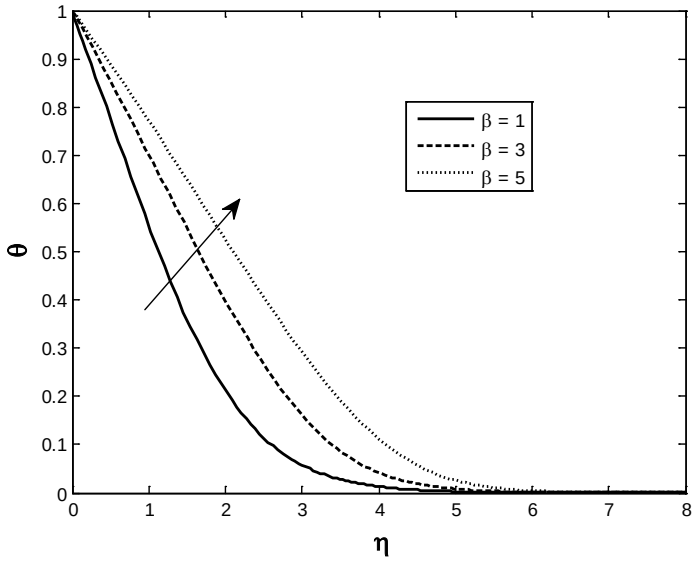

Fig-6: Temperature profile for different values of β for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and τ= 1

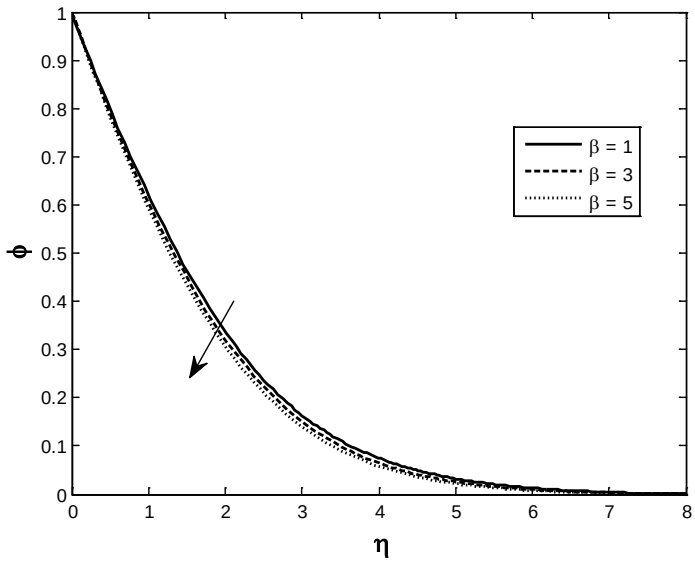

Fig-7: Concentration profile for different values of β for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and τ= 1

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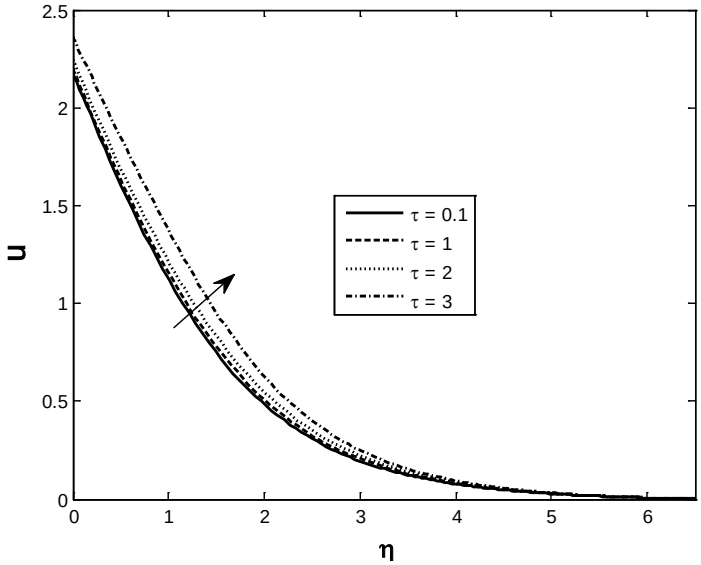

Fig-8: Velocity profile for different values of τ for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and β= 0.5

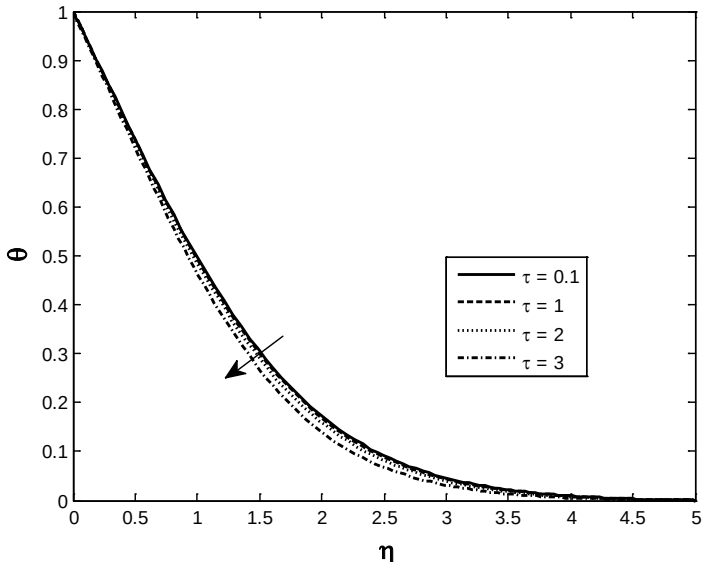

Fig-9: Temperature profile for different values of τ for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and β= 0.5

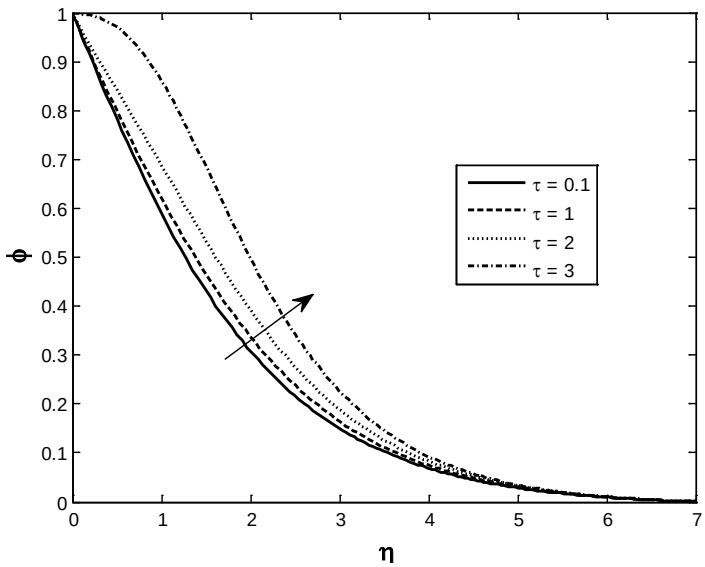

Fig-10: Concentration profile for different values of τ for N = 1, Le = 0.5, θ_r = 2, Sc = 0.6 and β= 0.5

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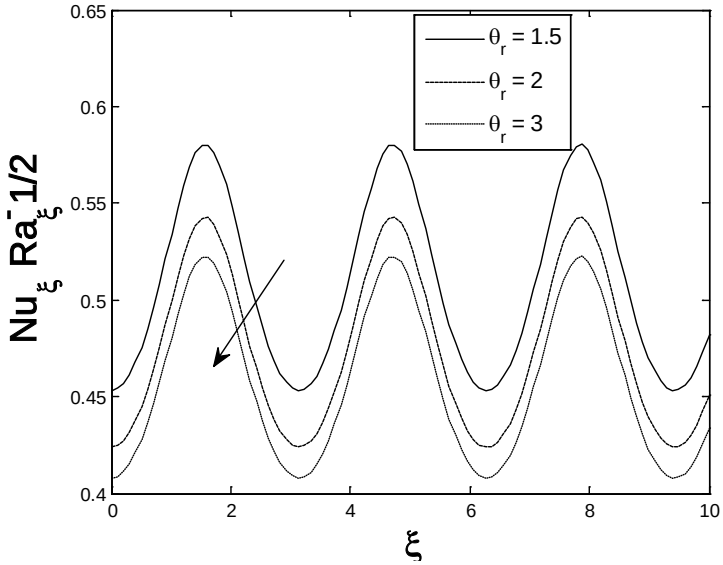

Fig-11: Axial distributions of the Nusselt number for different values of θ_r for N = 1, *a=0.5*, Le = 0.5, τ = 1, Sc = 0.6 and β= 0.5

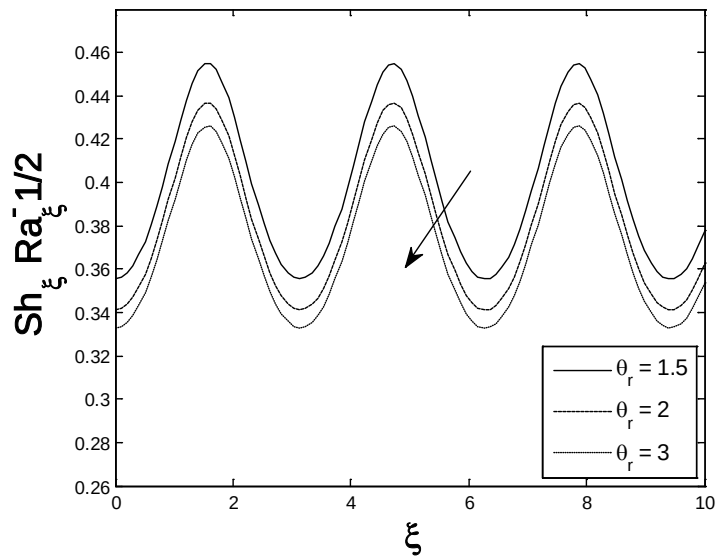

Fig-12: Axial distributions of the Sherwood number for different values of θ_r for N = 1, *a=0.5*, Le = 0.5, τ = 1, Sc = 0.6 and β= 0.5

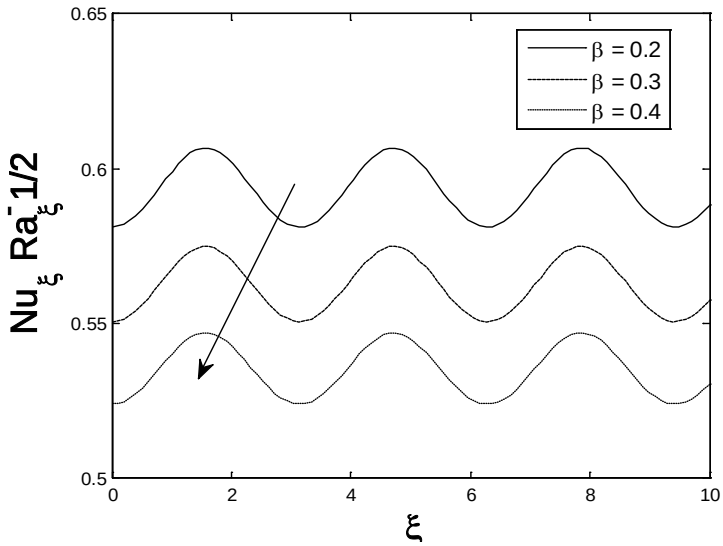

Fig-13: Axial distributions of the Nusselt number for different values of β for N = 1, Le = 0.5, *a=0.5*, τ = 1, Sc = 0.6 and θ_r= 1.5

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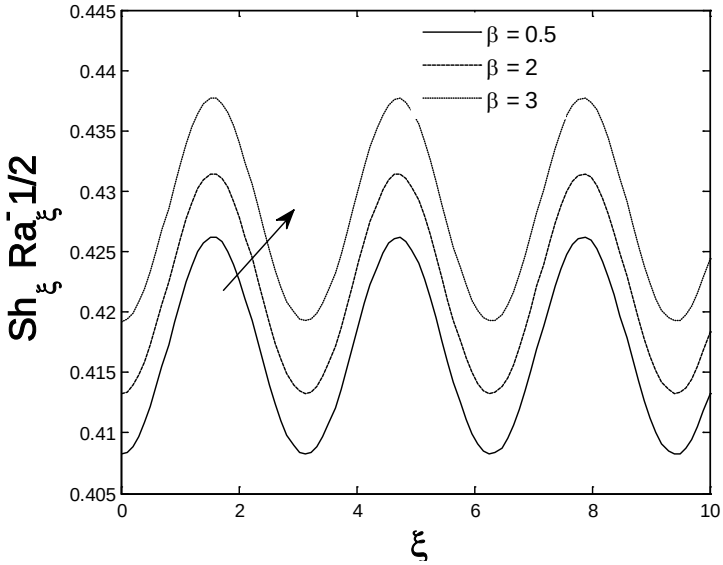

Fig-14: Axial distributions of the Sherwood number for different values of β for N = 1, *a=0.5*, Le = 0.5, τ = 1, Sc = 0.6 and θ_r= 1.5

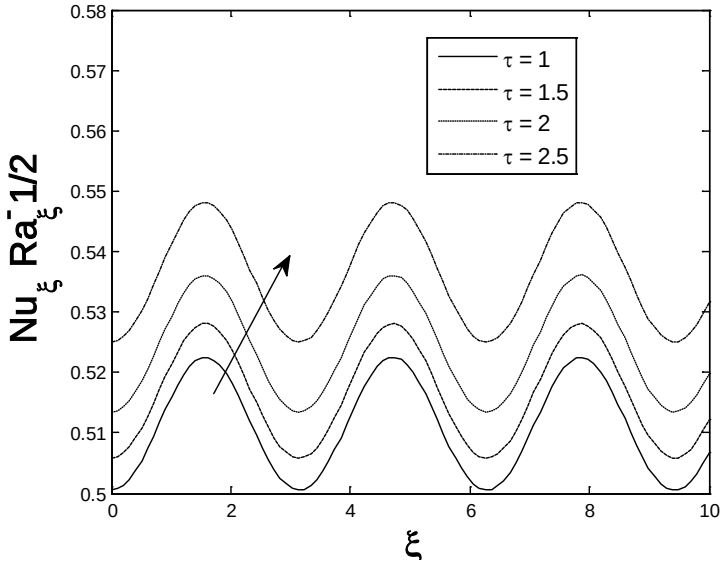

Fig-15: Axial distributions of the Nusselt number for different values of τ for N = 1, Le = 0.5, *a=0.5*, θ_r = 1.5, Sc = 0.6 and β= 0.5

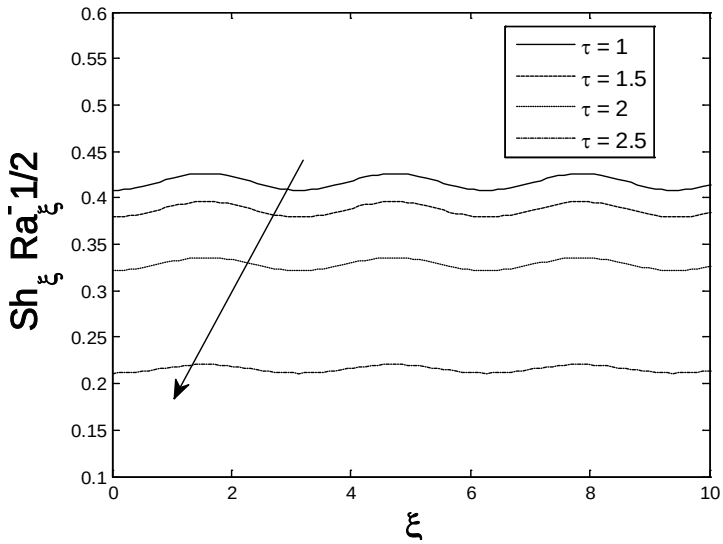

Fig-16: Axial distributions of the Sherwood number for different values of τ for N = 1, *a=0.5*, Le = 0.5, θ_r = 1.5, Sc = 0.6 and β= 0.5

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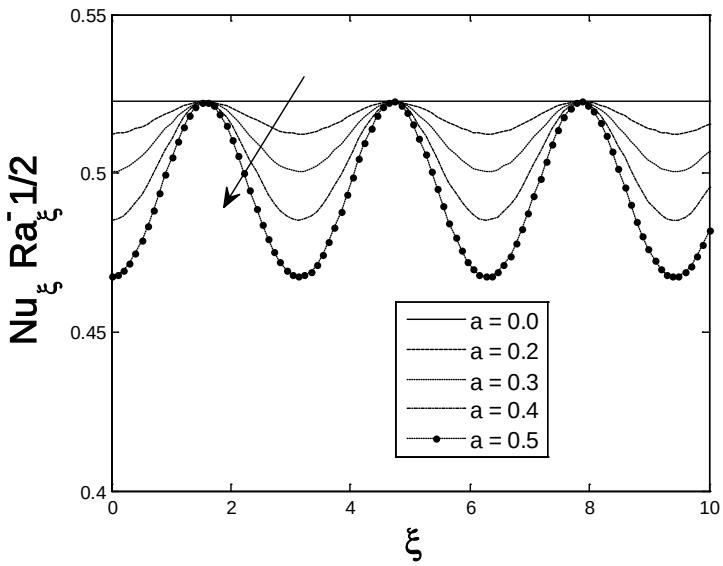

Fig-17: Axial distributions of the Nusselt number for different values of *a* for N = 1, Le = 0.5, τ = 1, θ_r = 1.5, Sc = 0.6 and β= 0.5

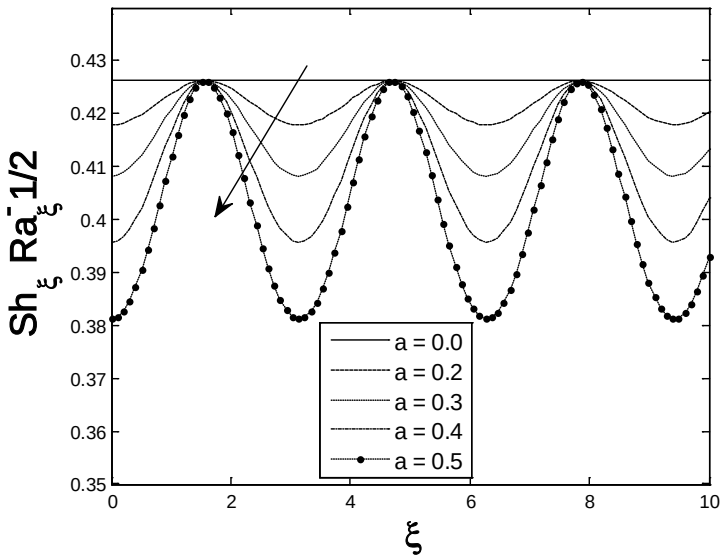

Fig-18: Axial distributions of the Sherwood number for different values of *a* for N = 1, τ = 1, Le = 0.5, θ_r = 1.5, Sc = 0.6 and β= 0.5

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