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Soret-Dufour Effects on Heat and Mass Transfer of Newtonian Fluid Flow over the Inclined Sheet and Magnetic Field

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ABSTRACT

Newtonian fluid is ideal for lubrication purposes because the viscosity of this fluid remains as a function of the shear. Besides, the heat and mass transfer are an important study area in fluid dynamics due to its vast applications in industrial processes. The heat-mass transfer can be defined as the Soret and Dufour effect, which implemented in many industrial applications such as in chemical engineering and geosciences field. In addition, the fluid flow over an extending/compressing sheet has significant industrial applications such as the cooling of continuous strips, glass fibre production, the extrusion of plastic sheets from a die, etc. As a response, this study aims to investigate the impacts of Soret and Dufour parameters on the Newtonian fluid flow over an inclined stretching/shrinking sheet. The methodology of this mathematical model are stated as follow: 1) the transformation of partial differential equations (PDEs) to the ordinary differential equations (ODEs), and 2) The ODEs are solved using bvp4c solver in MATLAB software. The bvp4c solver is a MATLAB program directory that solves general form and multi-point boundary layer problems. The main sections of bvp4c are: 1) The solution of the ODEs, 2) The related boundary conditions that can produce the expected results, and 3) An initial guess to run the bvp4c solver. As a result, the numerical and graphical results show that the Soret effect increases the concentration profile whereas decreases the temperature profile. The vice versa occurrence is true for Dufour effect. The convective mass transfer caused by a temperature gradient is known as thermal-diffusion (Soret) effect. The convective heat transfer produced by concentration differences is known as diffusion-thermo (Dufour) effect. However, since the process of heat and mass transfers are related to each other, the Soret and Dufour effects are able to influence both of this process simultaneously. In conclusion, the convective heat transfer is enhanced by increasing Soret and Dufour number while the convective mass transfer is declined by increasing the two numbers.

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1. Introduction

The linear viscosity law has categorized fluids into two either Newtonian or non-Newtonian. The examples of Newtonian fluid are water and air [1], and its application is cooking oil [2]. Therefore, a lot of theoretical and experimental research regarding to the heat transfer in the Newtonian fluid have been reported. The dimensions of the container or boundary of the Newtonian fluid model have been studied, such as rectangular cavity installed with three equally positioned semi-circular cylinders [3], in double-layered underground reservoir [4], rigid triaxial ellipsoid [5], rectangular microchannel [6], porous medium [7,8], and three-layered porous medium [9]. The types or patterns of the flow also being considered, such as Stokes flow [5], cross flow [8], turbulent flow [10], and shallow flow [11].

The transport of heat and mass when the fluid flowing occurs through concentration and temperature gradient. The heat and mass transfer plays vital roles in refrigerator compressor, air conditioner and automobiles engine [12]. The mass and heat transfers are produced due to the large gradients of fluid temperature and concentration, respectively. These diffusion are recognized as Soret effect (mass transfer) and Dufour effect (heat transfer). Thus, a lot of research carried out heat and mass transfer analysis, such as in the Newtonian fluid [13-16], Bingham fluid [17-19], Maxwell fluid [20-22], Casson fluid [23-25], etc. These fluid are bounded by a semi-circular cylinder [14], horizontal sheet [15,16,21,22,24,25], isothermal elliptical cylinder [17], heated rotating disk [18], vertical sheet [19], permeable cylinder [20], and a cylinder in a wavy channel [23].

Previous research, as mentioned in the above paragraph, did not study the fluid boundary layer model when the boundary surface is inclined. In addition, the heat-mass transfer model based on the Soret-Dufour simultaneous effect and when the fluid is affected by the inclined magnetic field is also not debated by the results of the above study. Therefore, this study is an extension of work done by Azmi *et al.,* [15], by applying the effect of when the vector of magnetic field is projected by a certain angle from a perpendicular direction from the stretching/shrinking sheet. The current study focuses on heat and mass transfer of Newtonian fluid with Soret-Dufour effects, where the fluid is flowing over an inclined stretching or shrinking sheet.

2. Methodology
2.1 Flow Model

The mathematical model of a Newtonian fluid are the 2D (*xy* plane) and has the feature of magnetohydrodynamics. The flow occurs over a shrinking sheet which is inclined to an angle of κ from $x-$ axis. The velocity components along x and y axes are denoted as u and v respectively. The ambient temperature and concentration of the fluid is denoted as T_∞ and C_∞. Meanwhile, the temperature and concentration on the surface of the sheet is denoted as T_w and C_w. The velocity $u_w(x)$ varies exponentially and the wall mass suction velocity denoted by $v_w(x)$ is assumed to be negative. The gravitational acceleration, g is acting downward to the model. The fluid flow model is illustrated in Figure 1.

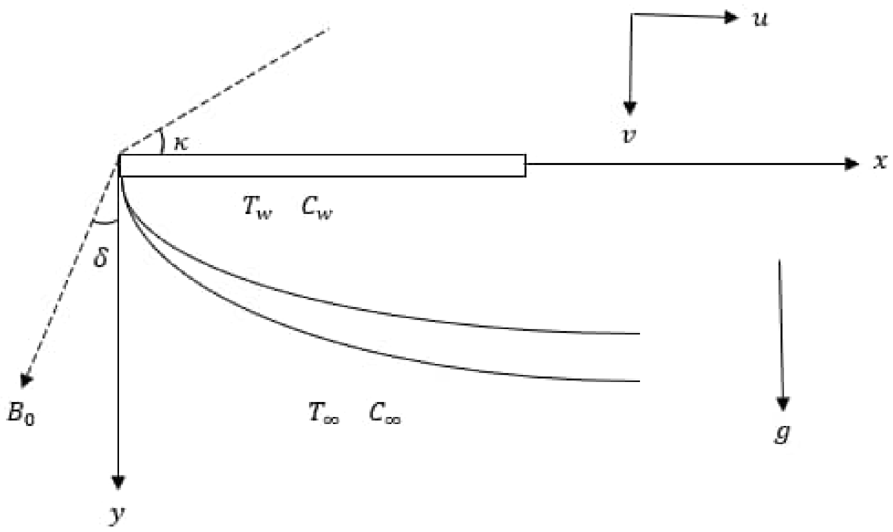

Fig. 1. The physical representation of current model

2.2 Continuity Equation

$$u_x = -v_y \tag{1}$$

The velocity components are defined as $u = \partial\psi/\partial y$ and $v = \partial\psi/\partial x$ where ψ refers to the stream function defined as

$$\psi(x, y) = (2\nu L U_0)^{\frac{1}{2}} e^{\frac{x}{2L}} f(\eta) \tag{2}$$

In addition, the definition of the boundary layer thickness η is expressed as in Eq. (3). This thickness is categorized as the momentum boundary layer thickness (the controlling factor for velocity profile), thermal boundary layer thickness (influence the temperature profile), and the concentration boundary layer thickness (the concentration profile is varied due to this type of thickness). This symbol also indicates the distance of the position whether exactly at the sheet ($\eta = 0$) or far from the sheet ($\eta \to \infty$).

$$\eta = y\left(\frac{U_0}{2\nu L}\right)^{\frac{1}{2}} e^{\frac{x}{2L}} \tag{3}$$

Using Eq. (2) and Eq. (3) to form u_x and v_y, then Eq. (1) is satisfied.

2.3 Momentum Equation

The momentum equation is presented as below, with the inclusion of the inclined magnetic field as innovated from Azmi *et al.,* [15]:

$$uu_x + vu_y = \nu u_{yy} + g\beta_T \cos\kappa(T - T_\infty) + g\beta_C \cos\kappa(C - C_\infty) - \frac{\sigma B_0^2(\sin^2\delta)u}{\rho} \tag{4}$$

Where $\nu = \mu/\rho$ refers to the kinematic viscosity, ρ refers to the density of fluid, g is the gravitational acceleration, β_T refers to the thermal expansion coefficient, κ is the sheet inclination angle, *T* refers to the temperature of fluid, β_C refers to the solutal expansion coefficient, *C* refers to the concentration of fluid, σ is the electrical conductivity, δ is the inclined angle of magnetic field, and B_0 is the magnetic field.

Eq. (5) are introduced to transform the partial differential equations into ordinary differential equations. The symbol of θ and φ are the temperature and concentration profiles, respectively. These profiles also responsible to increase or decrease the heat and mass transfer in the fluid flow model.

$$\theta = \frac{T-T_\infty}{T_w-T_\infty},\ \varphi = \frac{C-C_\infty}{C_w-C_\infty} \tag{5}$$

Using Eq. (3) and Eq. (5) with the involvement of Eq. (2), Eq. (4) is transformed as below.

$$f_{\eta\eta\eta} + f_{\eta\eta}f - 2(f_\eta)^2 - 2M(\sin^2\delta)f_\eta + 2R\,cos\kappa\,(\theta + G\varphi) = 0 \tag{6}$$

Here, $M = (\sigma L\beta_0^2 e^{-x/L})/(\rho U_0)$ is the magnetic field parameter and $R = Gr/Re^2$ is the mixed convection parameter where $Gr = (g\beta_T T_0 L^3 e^{x/2L})/\nu^2$ and $Re = (U_0 Le^{x/L})/\nu$ refers to the Grashof number and Reynolds number respectively. Next, $G = (\beta_C C_0)/(\beta_T T_0)$ refers to the buoyancy ratio.

2.4 Energy Equation

$$uT_x + vT_y = \frac{k}{\rho C_p}T_{yy} + \frac{K_T D_m}{C_p C_s}C_{yy} \tag{7}$$

Where k is the thermal conductivity, C_p is the specific heat at constant pressure, K_T is the thermal diffusion ratio, D_m is the solutal diffusivity of the medium, C_p is the specific heat at constant pressure, and C_s is the concentration susceptibility.

Repeating the similar process as momentum equation, the energy equations is transformed as below.

$$\theta_{\eta\eta} + \mathrm{Pr}[f\theta_\eta - f_\eta\theta + Db\varphi_{\eta\eta}] = 0 \tag{8}$$

$Pr = (\rho c_p \nu)/k$ is the Prandtl number and $Db = (D_m K_T C_0)/(C_s C_p \nu T_0)$ refers to the Dufour number.

2.5 Concentration Equation

$$uC_x + vC_y = D_m\left[C_{yy} + \frac{K_T}{T_m}T_{yy}\right] \tag{9}$$

By substituting the Eq. (2), (3), and (5), Eq. (9) is transformed as below,

$$\varphi_{\eta\eta} + Sc\left[Sr\theta_{\eta\eta} - f_\eta\varphi + f\varphi_\eta\right] = 0 \tag{10}$$

Where $Sc = \nu/D_m$ is the Schmidt number.

2.6 Boundary Conditions

The current flow model is governed by:

$$\begin{aligned} &u = u_w(x) = \lambda U_0 e^{x/L}, \quad v = v_w(x) \\ &T_w(x) = T_\infty + T_0 e^{x/2L}, \quad C_w(x) = C_\infty + C_0 e^{x/2L} && \text{at } y = 0, \\ &u \to 0, \quad T \to T_\infty, \quad C \to C_\infty && \text{as } y \to \infty. \end{aligned} \tag{11}$$

The shrinking sheet parameter is denoted by $\lambda < 0$. The wall mass suction velocity, $v_w(x) < 0$ and L refers to the reference length of the stretching/shrinking inclined sheet.

The Eq. (11) is also transformed by using Eq. (2), (3), and (5). The transformed boundary conditions are given as below,

$$\begin{aligned} &f_\eta = \lambda, \quad f = S, \quad \theta = 1, \quad \varphi = 1 && \text{at } \eta = 0, \\ &f_\eta \to 0, \quad \theta \to 0, \quad \varphi \to 0 && \text{as } \eta \to \infty. \end{aligned} \tag{12}$$

Suction parameter S is defined as $S = -\left(v_w(x) \times \sqrt{2L/\nu U_0}\right)/\left(e^{x/2L}\right) > 0$.

2.7 Physical Parameters

Nusselt number represents the temperature difference at the shrinking sheet, and the heat convection at this sheet can also be measured by calculating this parameter. The higher rate of heat convection is indicated by the higher value of Nusselt number. On the other hand, Sherwood number is defined as the mass convection of the shrinking sheet. Therefore, the usage of the word "local" in the Nusselt and Sherwood numbers considers the length to be the distance from the sheet boundary to the local point of interest. The local Nusselt number and local Sherwood number are defined as below,

$$Nu_x = [L/(T_w - T_\infty)]\left(-\frac{\partial T}{\partial y}\right)_{y=0} \tag{13}$$

$$Sh_x = [L/(C_w - C_\infty)]\left(-\frac{\partial C}{\partial y}\right)_{y=0} \tag{14}$$

The non-dimensional form of the physical parameters is obtained by substituting Eq. (3) and Eq. (5) into Eq. (13), (14) and (15), the following equations are obtained.

$$\sqrt{2/Re_X}\, e^{(-X/2)} Nu_X = -\theta_\eta(0), \qquad \sqrt{2/Re_X}\, e^{(-X/2)} Sh_X = -\varphi_\eta{}'(0). \tag{15}$$

3. Results and Discussion

3.1 Introduction

The built-in function in MATLAB software called bvp4c is the main technique to solve the ODEs. The following values of governing parameters are used throughout the study, unless stated otherwise: $S = 2.5, \kappa = 50°, \delta = 80°, \lambda = -0.4, R = -0.0212, Sc = 0.5, M = 0.4946, Db = 0.1002, G = 1.0585, \mathrm{Pr} = 1$ and $Sr = 1.8004$. The range of these values which are less than or greater than zero have these meaning: $S > 0$is the suction ($S < 0$ is the condition is when the injection is occurred at the sheet), $\lambda < 0$ is when the sheet is compressed directed to the origin of the *xy* dimension ($\lambda > 0$ is when the sheet is stretched towards +*x*- axis), and $R < 0$ is the opposing flow in the state of mixed convection ($R > 0$ is the assisting flow). Another parameter should be fixed in the positive values since they only consider the magnitude, not the direction.

The solution obtained for this model is a dual solution. The first solution is illustrated by solid line where the second solution is illustrated by dashed line. The effect of Soret $(Sr)$and Dufour (Db) parameters on the concentration profile $\phi(\eta)$, temperature profile $\theta(\eta)$, local Nusselt number $\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ and local Sherwood number $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$ are investigated by fixing three distinct values of those parameters. The comparison with the previous researcher have been tabulated in Table 1 for the values of she temperature gradient $-\theta_\eta(0)$ for various Pr and stretching sheet $\lambda = 1$ (other than these parameters are fixed as zero values). This table shows the good agreement among them.

Therefore, this section displays the numerical results regarding the effect of Soret and Dufour parameters in the variation of the temperature and concentration profiles, together with the physical parameters namely as local Nusselt number and local Sherwood number. All the graphs depicted are useful for explaining the characteristics of heat and mass transfer in this study.

Table 1
The comparison values for the temperature gradient of the sheet, varied by Pr number

Pr	Magyari and Keller [26]	Present
1.0	-0.95478	-0.954776
3.0	-1.86908	-1.869083
5.0	-2.50014	-2.500135

3.2 Effect of Soret Number

The Soret effect appears in the fluid particles due to the temperature gradient so that the particles with the high thermal energy will move from the hot region to the cold region. Therefore, mass transfer is induced due to the Soret effect. Since the Soret effect is also related with the temperature difference, it is also able to influence the characteristic of heat transfer. The amount of the mass and the temperature rate at the certain location can be displayed in the concentration and temperature profiles, which is subjected to the Soret effect. These profiles also can be influenced by the Dufour effect, since Dufour effect is associated with the heat transfer (this process is formed when there is a significant difference in concentration level between 2 regions).

The parameter Sr gives reverse effect on $\phi(\eta)$ and $\theta(\eta)$. As the Sr increases, both the first and second solution of $\phi(\eta)$ increases as the boundary layer becomes thicker. Meanwhile, the increment in this parameter decreases the temperature for both the numerical solutions. However, it is noticeable from Figure 2 that after a certain boundary layer thickness, the concentration starts to increase gradually for both the solutions. The distributions of $\phi(\eta)$ and $\theta(\eta)$ for rising values of Sr

can be explained by the relationship between them. The Soret number is directly proportional to the temperature gradient and inversely proportional to the concentration gradient. Thus, the temperature is decreased, and the concentration is enhanced when Sr is rising.

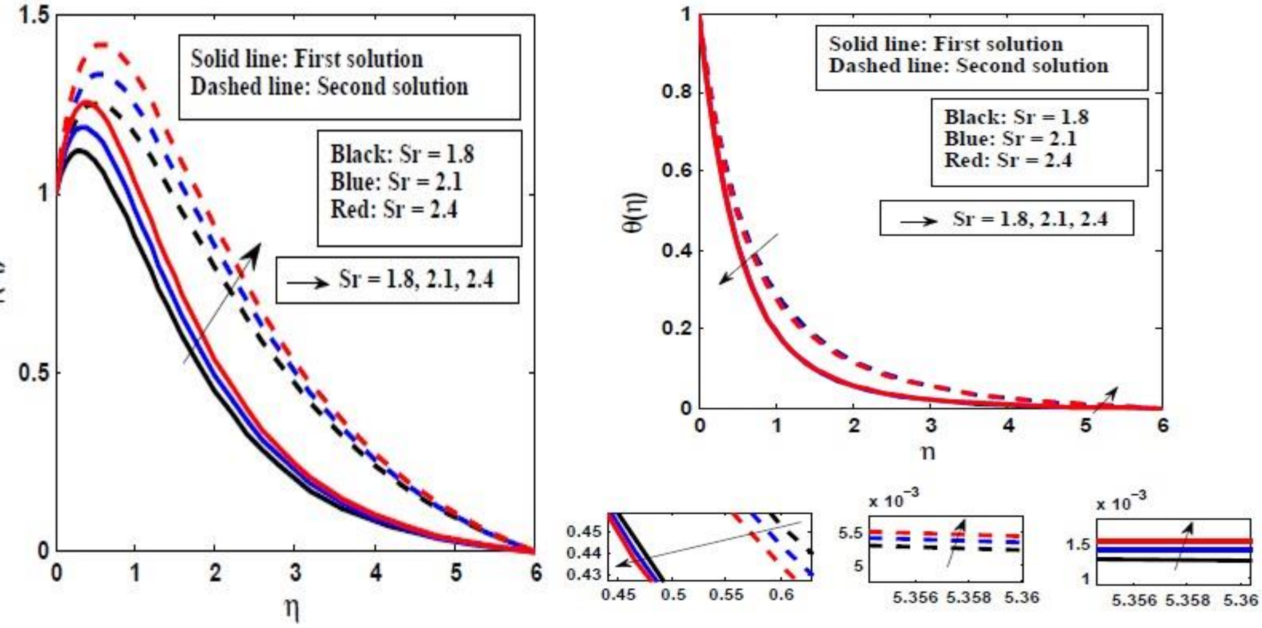

Fig. 2. Effect of Sr on the concentration profile (left side) and temperature profile (right side)

3.3 Effect of Dufour Number

Like Soret number, Dufour number (Db) also impacts the concentration and temperature profile oppositely, as shown in Figure 3. An increment Db makes the fluid less concentrated while makes the fluid much hotter. The Dufour number is directly proportional to the concentration gradient while inversely proportional to the temperature gradient. Thus, the fluid will become less concentrated and much hotter when Db is increased.

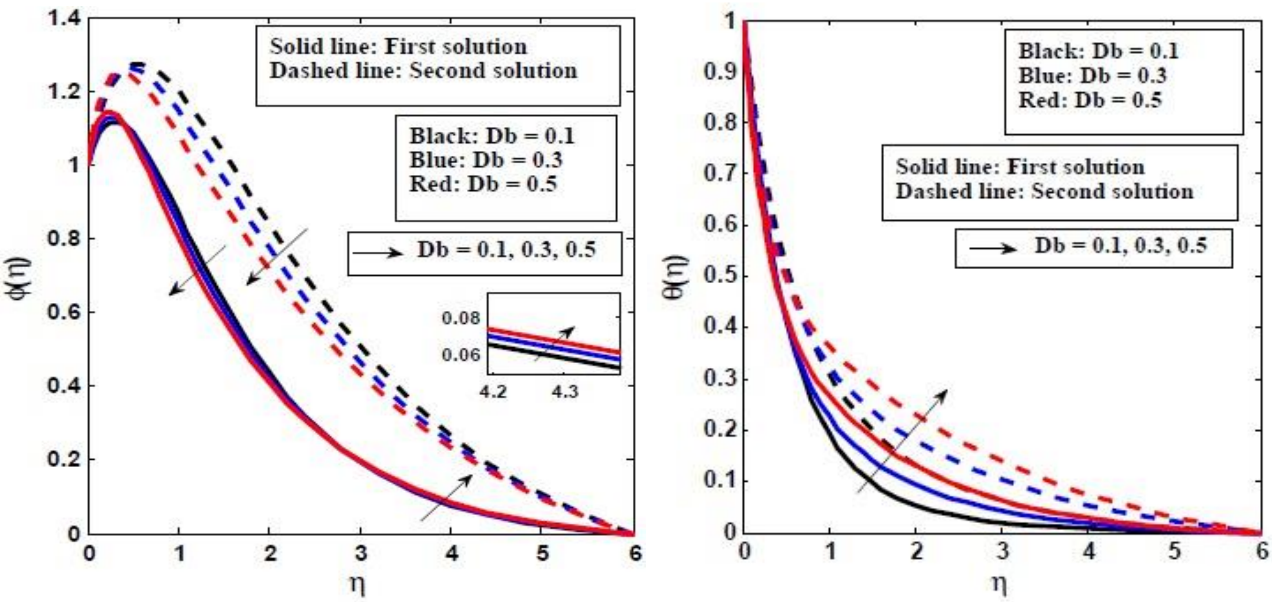

Fig. 3. Effect of Db on the concentration profile (left side) and temperature profile (right side)

3.4 Variation of Physical Parameters

The physical parameters ($\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ and $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$) are presented in Figure 4. The dual solutions for $\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ increases while $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$ decreases: This variation occurred as Sr and Db are increasing. Both solutions become close and will be equal to each other for highest Db ($Db = 0.9$) and when Sr is approaching the maximum value. This observation means that only the reliable numerical solution (without the unstable solution) is obtained for the certain values of Db and Sr.

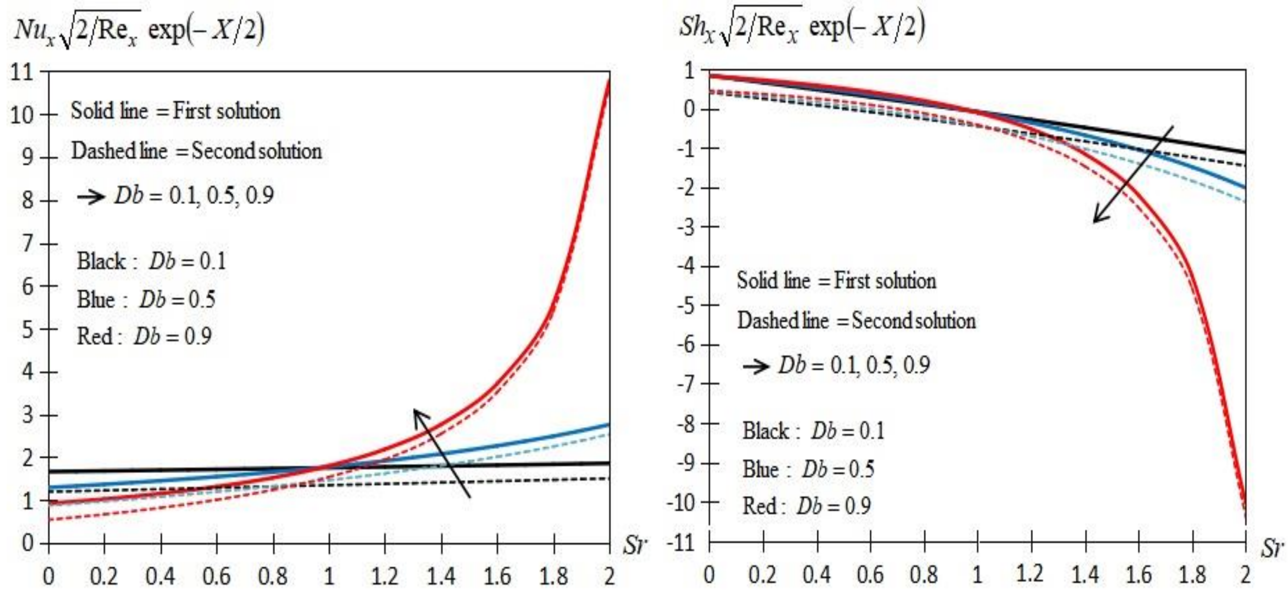

Fig. 4. The distributions of $\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ (left side) and $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$ (right side)

4. Conclusions

The objective of this study is to develop and solve numerically the mathematical model of the heat-mass transfer in Newtonian fluid. The sheet, which acts as a boundary of the fluid and magnetic field in this model also being projected by a certain angle from the perpendicular component of the model. Moreover, the effect of Soret and Dufour parameter are also considered. Therefore, this model is the current innovation from the previous studies regarding the exponential stretching sheet [26] and the boundary inclined sheet in the MHD boundary layer flow [15, 16, 21, 22, 24, 25] with the additional effect of inclined magnetic field. This boundary layer fluid flow model is restricted to the inclined shrinking sheet (negative λ), mixed convection where the fluid flow is opposed (negative R), and the suction effect is occurred at the shrinking sheet (positive S). In addition, the direction of the inclined sheet and the inclined magnetic field are in one direction of rotation (positive angle). The model is solved using bvp4c function provided by MATLAB software. The main findings of this study are summarized as follows:

i. The $\phi(\eta)$ profiles increases for increment in Sr while decreases for increment in Db.
ii. The $\theta(\eta)$ profile decreases as Soret number increases while increases as Db increases.
iii. As Sr increases, $\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ increases while $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$ decreases.
iv. As Db number increases, the $\sqrt{2/Re_X}e^{(-X/2)}Nu_X$ increases while $\sqrt{2/Re_X}e^{(-X/2)}Sh_X$ decreases.

Based on the main findings above, the temperature and concentration of the fluid can be controlled by the Soret and Dufour effect. Subsequently, these parameters can also govern the heat and mass transfer due to the large differences in the temperature and concentration profiles. This model can be extended to the unsteady state of the boundary layer flow in the non-Newtonian fluid, with other external factors such as thermal radiation, chemical reaction, etc.

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