Journal of Mines, Metals and Fuels, *73(5): 1321-1329; 2025. DOI: 10.18311/jmmf/2025/48680*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

**Contents available at:** *www.informaticsjournals.co.in/index.php/jmmf*

# Numerical Analysis of Soret and Dufour Effects in Two-Dimensional Williamson Fluid Flow Over a Stretching Surface

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## Abstract

*This study presents a comprehensive numerical analysis of the intricate interplay between Soret and Dufour effects within the two-dimensional Williamson fluid flow framework. The study investigates the behaviour of this non-Newtonian fluid as it interacts with non-linearly stretching surfaces, shedding light on the complex thermal and mass transfer phenomena at play. Our findings offer valuable insights into the underlying mechanisms governing these effects, providing a pivotal contribution to the field of fluid dynamics and its applications in advanced engineering systems. A study on the flow dynamics of a Williamson nanofluid over a nonlinear stretching sheet was conducted using numerical simulations. Key phenomena like Brownian motion, diffusion thermo, thermal diffusion, and thermophoresis were examined. The finite element method was used to solve the complex equations and their boundary conditions. The research examined the impact of various technical parameters on temperature, concentration and velocity profiles. The findings were documented and accompanied by graphical representations. The results were found to be valid and relevant within the context of fluid dynamics and nanofluid studies, contributing significantly to understanding nanofluid behavior under complex conditions and paving the way for future research and applications in advanced thermal management systems.*

**Major Findings:** *The study explores the relationship between non-Newtonian fluid behavior and nonlinearly stretching surfaces, focusing on thermal and mass transfer processes. Key parameters were examined to understand temperature, concentration, and velocity profiles. The analysis provides valuable insights into the underlying mechanisms, contributing to fluid dynamics, especially in nanofluid applications. The findings are valid and relevant within fluid dynamics and nanofluid research, providing a deeper understanding of nanofluid behavior under complex conditions. This research enhances our understanding of fundamental processes and lays the groundwork for future thermal management system design and optimisation.*

**Keywords:** *Dufour, MHD, Nanofluid, Non-Linearly Stretching Sheet, Soret, Williamson Fluid*

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## 1.0 Introduction

Understanding heat and mass transfer phenomena in fluids is crucial for technical and scientific applications, especially in complex fluid systems. The Soret and Dufour effects, named after French scientist Charles Soret and engineer Georges Dufour, describe mass transfer due to temperature differences and thermal energy transfer resulting from concentration gradients. These effects are intensified by temperature and concentration gradients in multicomponent systems. Nano fluids, colloidal suspensions of nanoparticles in a base fluid, add complexity due to their interactions with the fluid. Williamson fluids, non-Newtonian, often display shear-thinning or shear-thickening behaviors due to their viscoelastic properties. The unique characteristics of nano and Williamson fluids create intricate fluid dynamics critical in fields like materials science, chemical engineering, biotechnology, and nanotechnology. Accurate modeling and forecasting of these behaviours are essential for developing effective processes.

Recent studies have made significant contributions to this area. For instance, Wang and Mujumdar in their research explored the applications of nanofluids, while Jafari *et al.*,[1] examined the Magnetohydrodynamic (MHD) flow of graphene nanoparticle-containing fluids. Nadeem *et al.*[2] investigated the MHD flow of Williamson nanofluids over an exponentially stretched sheet, and Sheikholeslami and Ganji[3] provided analytical solutions for MHD nanofluid flow in porous media, considering thermophoresis and Brownian motion. Other notable studies include Rana and Bhargava[4], who studied heat and mass transfer in Williamson nanofluids, and Farooq *et al.* [5], who simulated the flow of Williamson nanofluids across a stretched sheet. Articles[6,13] and[14] provide some instances of potential uses. Numerous significant investigations undertaken in this domain are included in the references[7-12]. The works mentioned in the literature[13-24] had a substantial impact on understanding the nature of the reported work and the authors[25-36] have shown the Finite Element Method (FEM) solutions for the heat and mass transfer problems in different cases.

This study examines the impact of thermal diffusion and diffusion thermo on the flow of a non-Newtonian Williamson fluid along a non-linearly stretching sheet. It incorporates factors like magnetic fields, thermal diffusion, Lewis number, and diffusion thermo using numerical solutions. While looking at the model, all its physical qualities were listed. This was done before looking at the physical properties of the problem. Governing equations and essential principles were used to build the issue. The results were presented through graphs and tabular data for engineering parameters. Comparisons with existing literature show strong agreement with findings obtained through the FEM approach.

## 2.0 Flow Modelling and Governing Equations

The flow of an MHD Williamson nanofluid across a non-linear stretching sheet with Soret and Dufour effects present has been modeled and examined in this study. The fundamental steady state, mass, momentum, thermal energy, and nanoparticle equations are all part of the Williamson-Nanofluids equations. The following are the governing equations.

Continuity Equation:

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

Momentum Equation:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\left(\frac{\partial^2 u}{\partial y^2}\right)+\sqrt{2}\Gamma\left[\frac{\partial u}{\partial y}\right]\left[\frac{\partial^2 u}{\partial y^2}\right]-\left(\frac{\sigma B_o^2}{\rho}\right)u, \tag{2}$$

Equation of thermal energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial y^2}\right)+\tau_B\left\{D_B\left[\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right]+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\}+\frac{D_m K_T}{C_s C_p}\left(\frac{\partial^2 C}{\partial y^2}\right) \tag{3}$$

Equation of nanoparticle concentration:

$$u\left(\frac{\partial C}{\partial x}\right)+v\left(\frac{\partial C}{\partial y}\right)=D_B\left(\frac{\partial^2 C}{\partial y^2}\right)+\left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{D_m K_T}{T_m}\left(\frac{\partial^2 T}{\partial y^2}\right), \tag{4}$$

Williamson-nanofluid flow's conditions are

$$\left.\begin{array}{l} u=u_w=ax^n, v=0, T=T_w, C=C_w \ \ at\ y=0 \\ u\to 0,\ v\to 0,\ T\to T_\infty,\ C\to C_\infty \ \ as\ y=\infty \end{array}\right\} \tag{5}$$

Proposed similarity variables are as below

$$\left.\begin{aligned} n &= y\left(\sqrt{\frac{a(n+1)}{2\nu}}\right)x^{\frac{n-1}{2}},\ u = ax^n f'(n), \\ \nu &= -\left(\sqrt{\frac{a\nu(n+1)}{2}}\right)x^{\frac{n-1}{2}}\left(f(n)+\left(\frac{n-1}{n+1}\right)nf'(n)\right), \\ \theta(n) &= \frac{T-T_\infty}{T_w-T_\infty},\ \phi(n) = \frac{C-C_\infty}{C_w-C_\infty} \end{aligned}\right\} \quad (6)$$

By (6), (2),(3) and (4) will get the following form

$$f''' + ff'' - \left(\frac{2n}{n+1}\right)f'2 - mf' + \lambda f'' f''' = 0 \quad (7)$$

$$\theta'' + \Pr f\theta' + \Pr Nb\theta'\phi' + \Pr Nt\theta'^2 + \Pr Du\phi'' = 0 \quad (8)$$

$$2Nb\phi'' + NbLef\phi' + 2Nt\theta'' + 2NbSr\theta'' = 0 \quad (9)$$

From the above,(5) takes the following conditions

$$\left.\begin{aligned} &f = 0,\ f' = 1,\ \theta = 1,\ \phi = 1,\ at\ n = 0 \\ &f' \to 0,\ \theta \to 0,\ \phi \to 0,\ as\ n = \infty \end{aligned}\right\} \quad (10)$$

where the involved physical parameters are defined as

$$\left.\begin{aligned} &\Pr = \frac{\nu}{\alpha},\ M = \frac{\sigma B_o^2 x}{\rho a},\ Le = \frac{\nu}{D_B}, \\ &Nb = \frac{(\rho C)_p D_B (C_w - C_\infty)}{(\rho C)_f \nu},\ \lambda = \Gamma x\sqrt{\frac{2a^3}{\nu}}, \\ &Sr = \frac{D_m K_T (T_w - T_\infty)}{T_m \nu (C_w - C_\infty)},\ Du = \frac{D_m K_T (C_w - C_\infty)}{C_s C_p \nu (T - T_\infty)}, \\ &Nt = \frac{(\rho C)_p D_T (T_w - T_\infty)}{(\rho C)_f \nu T_\infty}, \end{aligned}\right\} \quad (11)$$

Engineering quantities

$$Cf = \frac{\tau_w}{\rho u_w^2} = \frac{\mu}{\rho u_w^2}\left(\frac{\partial u}{\partial y} + \frac{\Gamma}{\sqrt{2}}\left(\frac{\partial u}{\partial y}\right)^2\right)_{y=0}$$

$$\Rightarrow \left(\sqrt{\mathrm{Re}_x}\right)Cf = f''(0)\left(1 + \frac{\lambda}{2}f''(0)\right) \quad (12)$$

$$Nu_x = \frac{xq_w}{\kappa(T_w - T_\infty)} \text{ where}$$

$$q_w = -\kappa(T_w - T_\infty)x^{\frac{n-1}{2}}\left(\sqrt{\frac{a(n+1)}{2\nu}}\right)\theta'(0)$$

$$\Rightarrow Nu_x = -x^{\frac{n+1}{2}}\left(\sqrt{\frac{a(n+1)}{2\nu}}\right)\theta'(0) \quad (13)$$

$$Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)}$$

$$\Rightarrow Sh_x = -x^{\frac{n+1}{2}}\left(\sqrt{\frac{a(n+1)}{2\nu}}\right)\phi'(0) \quad (14)$$

## 3.0 Method of Solution

Numerical modelling and simulation are more efficient and cost-effective methods for solving complex mathematical equations than traditional methods. These models accurately represent the physical system under investigation, allowing for rigorous analysis and validation against real-world observations. The FEM used in this study, is a versatile and powerful technique for addressing linear and nonlinear Partial Differential Equations (PDEs). It is a valuable tool for future research in fields like physics and mechanical engineering, and its applicability extends to a broad range of complex systems, indicating continued progress in these fields. The numerical solution for a flow, heat, and mass transfer problem is obtained using Mathematica, using the FEM. The steps invovled in FEM is shown in the following Figure 1.

## 4.0 Results and Discussion

The present mathematical model includes Williamson-Nanofluid, and the effects of Brownian motion, thermal

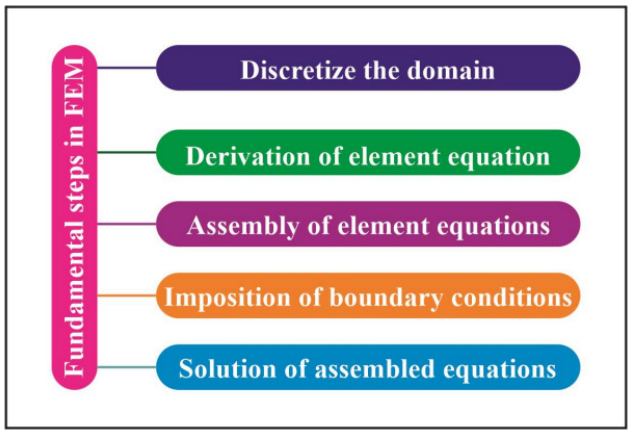



**Figure 1.** Steps involved in FEM.

diffusion, diffusion thermo, and thermophoresis are examined using the same boundary conditions. For this physics topic, there are three primary nonlinear PDEs. They are the equations for motion, energy, and concentration. Similarity functions are used to create a collection of nonlinear Ordinary Differential Equations (ODEs). They are then solved using the finite element approach, which provides us with exact solutions that take the boundary conditions into account. The effects of various factors on the outcomes are examined.

A detailed analysis of the flow of fluids in a fluid system, focusing on various factors such as Magnetic Field measure (M), Williamson fluid parameter (λ), Weissenberg number (λ), and the Prandtl number (Pr), is presented in this section. As shown in Figure 2, the M and the Weissenberg number (We) are used to analyse viscous flows, with the latter representing the magnetic field. As the M increase, the velocity curve decreases due to the retarding force, which slows down the fluid's flow. In Figure 3, the Williamson fluid parameter (λ), also known as the Weissenberg number (λ), changes as the speed curve does, indicating how elastic and viscous forces compare. The Weissenberg number (We) increases as the fluid's rest time grows, making it harder for the flow to move. It can be seen in Figure 4. The values of the stretching parameter (n) change for different non-linear stretching parameters, resulting in more regular motion curves. The temperature of the fluid is affected by the Prandtl number (Pr), which increases as Pr rises, making it harder to see the factors that change the rate at which the fluid's temperature changes. This is because the Prandtl number increases momentum diffusivity while decreasing temperature diffusivity, as shown in Figure 5.

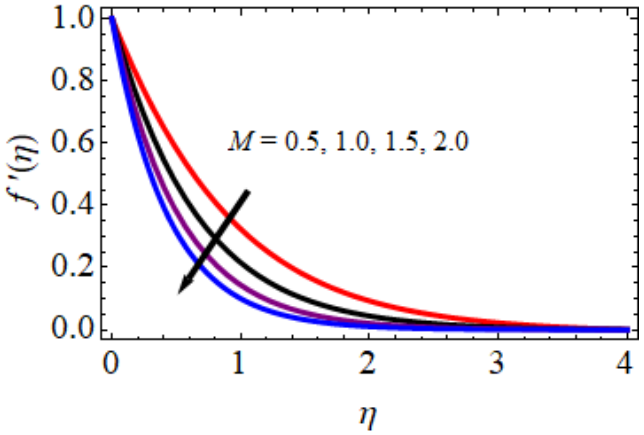



**Figure 2.** *M* effect on velocity profiles.

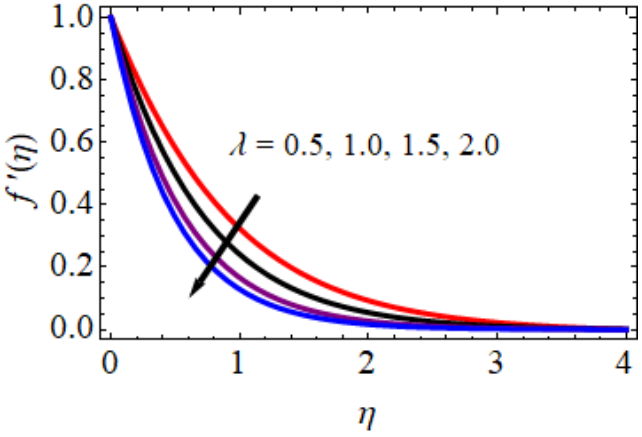



**Figure 3.** $\lambda$ effect on velocity profiles.

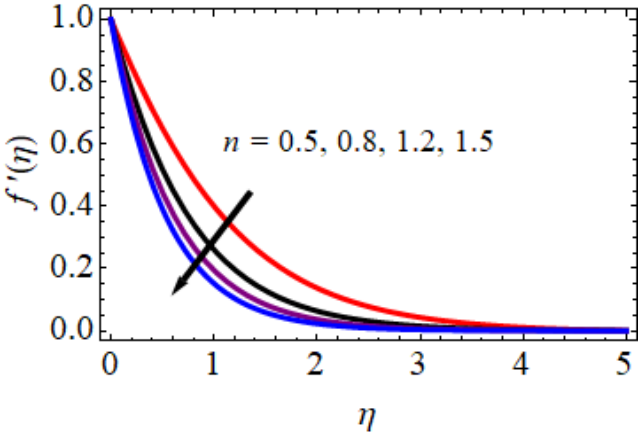



**Figure 4.** *n* effect on velocity profiles.

As shown in Figures 6 and 7, the Brownian motion parameter (Nb) is connected to the temperature and concentration curves, with the temperature profiles getting closer together as the Brownian motion measure goes up, but the concentration profiles get further apart. As shown in Figures 8 and 9, the Thermophoresis parameter (Nt) changes with profiles of temperature and concentration, with the predicted parameter Nt changing the temperature profiles, concentration profiles of nanoparticles, and the sizes of the boundary layers. When Nt is raised, concentration overflow happens, causing both the fluid's temperature and the number of nanoparticles to rise. As shown in Figure 10, the temperature curve of the fluid increases as the Dufour number (Du) goes up, causing a larger temperature difference inside the system. From Figure 11, it can be seen that the Soret number (Sr) changes the way concentration patterns look, with the Soret effect occurring when there is a difference in temperature in a

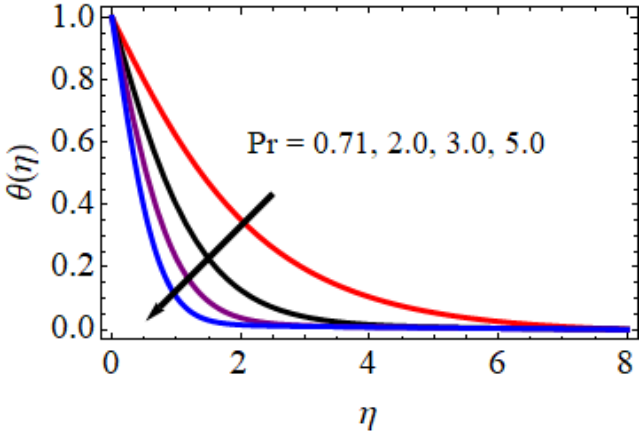



**Figure 5.** Pr effect on temperature profiles.

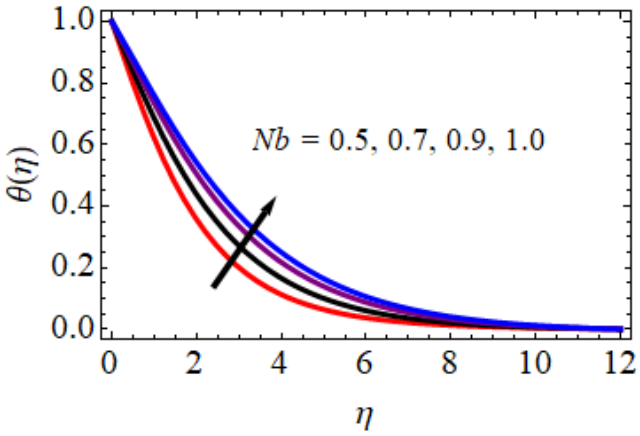



**Figure 6.** *Nb* effect on temperature profiles.

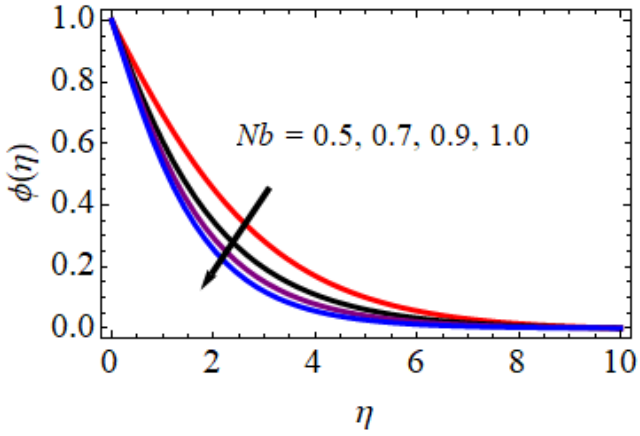



**Figure 7.** *Nb* effect on concentration profiles.

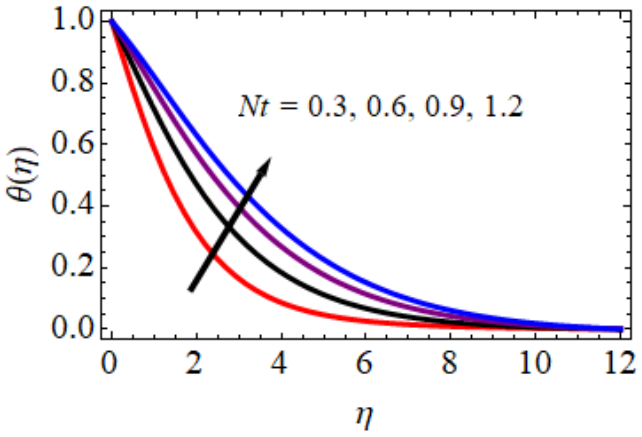



**Figure 8.** *Nt* effect on temperature profiles.

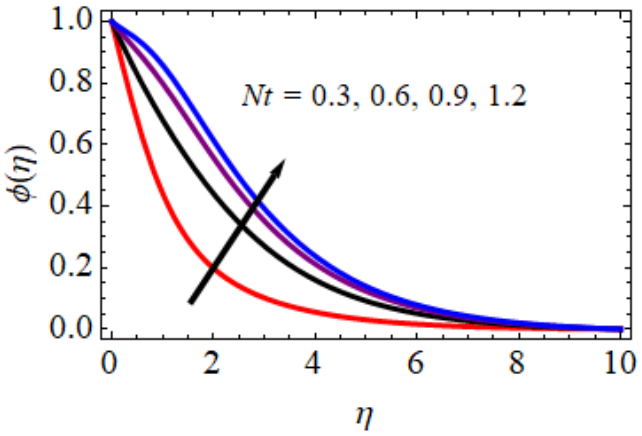



**Figure 9.** *Nt* effect on concentration profiles.

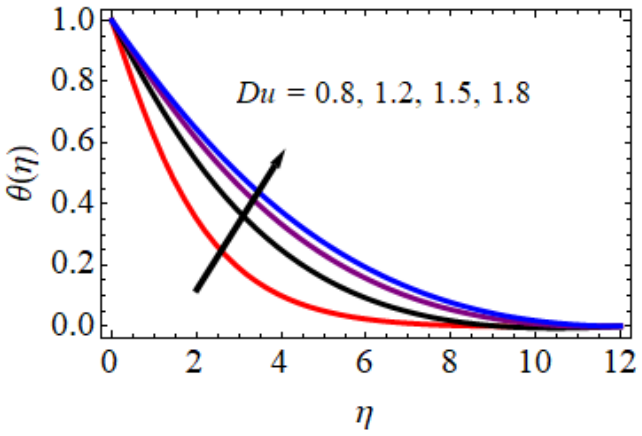



**Figure 10.** *Du* effect on temperature profiles.

concentration field due to processes that cannot be undone. The Lewis number (Le) is the measure of how easy it is for heat to move through a nanofluid compared to how easy it is for mass to move through it. As the number of Le rises, the share of nanoparticle volume decreases, as can be seen in Figure 12. Table 1 shows the skin-friction coefficient changes depending on several scientific factors, including the Soret number (Sr), Dufour number (Du), Lewis

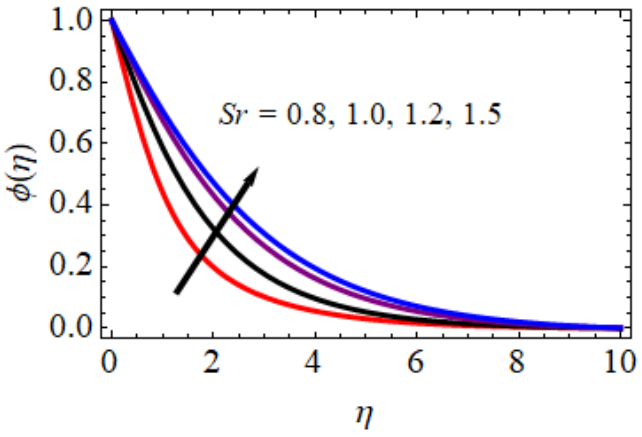



**Figure 11.** *Sr* effect on concentration profiles.

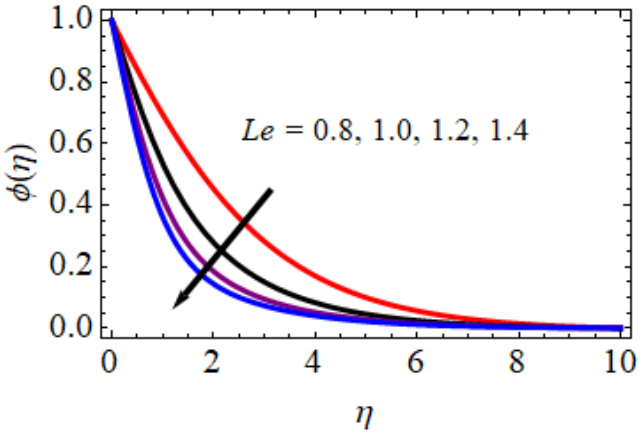



**Figure 12.** *Le* effect on concentration profiles.

number (Le), Stretching sheet parameter (n), Williamson fluid parameter (λ), Thermophoresis parameter (Nt), Brownian motion parameter (Nb), Prandtl number (Pr), and Thermophoresis parameter (Nt). The skin-friction coefficient increases when the thermophoresis parameter (Nt), Brownian motion parameter (Nb), Dufour number parameter (Du), Soret number parameter (Sr), and thermophoresis parameter (Nt) all go up. Table 3 in this text provides information on the heat transfer coefficient rate, utilising the Nusselt number and highlighting various components such as Brownian motion parameter (Nb), Dufour number parameter (Du), Prandtl number (Pr), and thermophoresis parameter (Nt). The heat transfer coefficient increases with the values of these parameters, while the Prandtl number decreases with increasing values.

Table 4 demonstrates the influence of various parameters on the Sherwood number coefficient, including the Lewis number, Soret number parameter,

**Table 1.** Numerical values of skin friction coefficient

| *n* | *M* | **Pr** | *Nt* | *Nb* | *Sr* | *Du* | *Le* | **λ** | *Cf* |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.5 | 0.71 | 0.3 | 0.5 | 0.8 | 0.8 | 0.8 | 0.5 | 1.5695676450 |
| **0.8** | | | | | | | | | 1.5357626503 |
| **1.2** | | | | | | | | | 1.5167686742 |
| | **1.0** | | | | | | | | 1.5256768719 |
| | **1.5** | | | | | | | | 1.5067656876 |
| | | **2.00** | | | | | | | 1.4856561981 |
| | | **4.00** | | | | | | | 1.4647648760 |
| | | | **0.6** | | | | | | 1.5982598225 |
| | | | **0.9** | | | | | | 1.6257683476 |
| | | | | **0.7** | | | | | 1.6045828712 |
| | | | | **0.9** | | | | | 1.6256768749 |
| | | | | | **1.0** | | | | 1.6358235892 |
| | | | | | **1.2** | | | | 1.6576658714 |
| | | | | | | **1.2** | | | 1.6413790941 |
| | | | | | | **1.5** | | | 1.6668768151 |
| | | | | | | | **1.0** | | 1.5476872762 |
| | | | | | | | **1.2** | | 1.5244343640 |
| | | | | | | | | **1.0** | 1.5300096763 |
| | | | | | | | | **1.5** | 1.5108762283 |

**Table 2.** Rate of heat transfer coefficient values

| **Pr** | *Nt* | *Nb* | *Du* | $Nu_x$ |
|---|---|---|---|---|
| 0.71 | 0.3 | 0.5 | 0.8 | 1.1257825823 |
| **2.00** | | | | 1.1568971547 |
| **4.00** | | | | 1.1807967398 |
| | **0.6** | | | 1.1659877926 |
| | **0.9** | | | 1.1906063755 |
| | | **0.7** | | 1.1591026227 |
| | | **0.9** | | 1.1856930570 |
| | | | **1.2** | 1.1656765761 |
| | | | **1.5** | 1.1904865651 |

**Table 3.** Rate of mass transfer coefficient values

| *Le* | *Nt* | *Nb* | *Sr* | $Sh_x$ |
|---|---|---|---|---|
| 0.8 | 0.3 | 0.5 | 0.8 | 1.2389560752 |
| **1.0** | | | | 1.2097244209 |
| **1.2** | | | | 1.1894626812 |
| | **0.6** | | | 1.2698709622 |
| | **0.9** | | | 1.2845887215 |
| | | **0.7** | | 1.2195158685 |
| | | **0.9** | | 1.1905626501 |
| | | | **1.0** | 1.2646783873 |
| | | | **1.2** | 1.2952878120 |

Brownian motion parameter, thermophoresis parameter and Lewis number.

## 5.0 Conclusion

With potential use in the industrial heat and mass transfer processes, this work presents a novel analysis of heat and mass transfer inside a Williamson nanofluid across a stretched sheet, analysing the impacts of Dufour and Soret on flow control. The research paves the way for tailored nanofluid systems in fields like chemical reactors and microelectronics cooling, where exact control over heat and mass transmission is crucial. The findings emphasise how crucial it is to properly assess nanoparticle concentrations to enhance heat transfer pathways. Further study and understanding of these mechanisms are necessary to maximise heat transfer performance in practical applications. The work employs a computer-based FEM Technique to solve basic nonlinear coupled ordinary differential equations. As the stretched sheet parameter, the Williamson fluid material parameter, and the magnetic field parameter increase, the velocity distribution gets smaller. As the Dufour, Thermophoresis, and Brownian motion numbers rise, so do the temperature profiles. When the Prandtl number rises, the temperature profiles fall. As Soret number and thermophoresis parameters increase, concentration increases; yet, as Lewis number and Brownian motion parameters increase, concentration decreases. The results are compared to those that are publicly available and frequently show agreement.

## 6.0 Industrial Applications of the Present Study

The study of Williamson fluid flow over a stretching sheet is essential in polymer extrusion and plastic sheet manufacturing. The Soret effect enhances mass diffusion, improving product uniformity. In metal fabrication, thermal and concentration gradients significantly affect material quality. The Dufour effect impacts heat transfer during alloy processing and welding. Soret and Dufour effects influence mass diffusion and heat transport in thin-film deposition, which is crucial in semiconductor manufacturing. Microchannel cooling in electronics involves non-Newtonian fluids where thermodiffusion impacts temperature control. Heat and mass transfer phenomena in solar energy systems, including the Soret and Dufour effects, optimise fluid flow efficiency.

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