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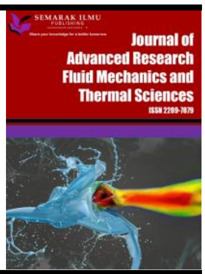

Squeezing MHD Flow of Sodium Alginate-Based Casson Hybrid Nanofluid with Soret and Dufour Effects

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ABSTRACT

Ultrahigh-performance cooling is one of the essential requirements in the industrial technology. Hence, the new heat transfer fluid, hybrid nanofluid is introduced to increase the thermal conductivity of fluid and investigated with various physical parameters. The unsteady magnetohydrodynamics (MHD) flow of Casson hybrid nanofluid through two surfaces in a permeable medium with chemical reaction are explored. The hybrid nanoparticles of Alumina (Al_2O_3) and Copper (Cu) is dispersed in the base fluid of sodium alginate $(C_6H_9NaO_7)$. The discretize equations are solved using similarity transformation and Keller-box methods. The comparison of the current results with the published results for validation is conducted and discovered in proper agreement. The impacts of squeeze, magnetic, porous media, chemical reaction, heat sink/source, and Soret and Dufour on behaviour and physical quantities of flow are discussed. The graphical results show the squeeze of two surfaces accelerates the fluid velocity near the upper plate region. Further, the velocity slowing down when β and Ha increases, and it elevates as Da and ϕ_2 rises in the middle of channel. The increment of heat transfer rate and temperature of fluid is shown for increasing Ec, γ and Du, and the opposite behaviour is discovered with raise in ϕ_2. The fluid concentration decreases and the mass transfer rate enhances for rising Sr. The concentration enhance and rate of mass transfer reduce with the constructive chemical reaction, whereas contrary effects is shown for destructive chemical reaction.

1. Introduction

Compression and decompression of fluid within two plates is known as squeezing flow. Many scientists have keen interest on the field of squeeze flow due to the application in hydraulic lifts, lubrication system and injection moulding [1]. The research on the squeeze flow of viscous fluid over horizontal plates is pioneered by Stefan [2]. Then, Cameron [3] continued the study by considering infinite plates. A new similarity variable was introduced by Wang [4] for converting Navier-Stokes equations to ordinary differential equations on the studies of squeeze flow of viscous fluid. Next, the

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researches of Wang [4] was conducted by Bujurke *et al*., [5], Rashidi *et al*., [6] and Khan *et al*., [7] analytically.

The significance of the researches on the non-Newtonian flow has been acknowledged by scientists due to its implementation on engineering industries. Casson fluid is known as shear thinning flow because of high yield stress and shear viscosity [8]. Commonly, the fluid acting as solid, but it starts to flow if the strong force is imposed on the fluid. The motion of pigment oil suspension is explored using Casson fluid model by Casson [9]. Later, Khan *et al*., [10] introduced the research on time dependent Casson fluid flow by squeezing two surfaces. Ahmed *et al.,* [11] studied the effects of magnetic field on electrically conducted Casson fluid on the squeezing plates. The work from Khan *et al*., [12] was extended by Ahmed *et al*., [11] with addition of permeable medium. The joule dissipation impact on squeezing of Casson fluid flow is reviewed by Mohyud-Din *et al*., [13].

The influences of magnetohydrodynamics (MHD) on the flow is discovered in various geometrical models of fluid. The magnetic field exerted on the electrical conduction fluid produces the Lorentz force. It is often arising in the medical and engineering usages, for instance, it functions as transporter for magnetic drug inside the body, cyclotrons and mass spectrometer [14]. The MHD flow by squeezing of two plates was examined by Siddiqui *et al*., [15] and resolved via homotopy perturbation method (HPM). The similar problem is solved by Sweet *et al*., [16] through homotopy analytical method (HAM) with variation of fluid density and magnetic field. The flow of squeeze Casson fluid under influence of MHD was investigated by Ahmed *et al*., [10]. The new approximate analytical solution according to power series coefficients is used by Al-Saif and Jasim [17] to solve the similar problems. The flow on the porous medium is important in the such as thermal energy storage, nuclear reactors oil extraction, geothermal energy recovery and plasma studies [18]. The impacts of MHD on squeezing Casson flow across permeable medium was explored by Khan *et al*., [12]. The slip condition on squeezing MHD of Casson flow over permeable medium was done by Qayyum *et al*., [19]. Later, Sobamowo *et al*., [20] discovered squeezing Casson nanofluid flow on permeable media under magnetic field impacts via Tiwari and Das model.

The application of heat transfer fluid in various thermal devices is acknowledged by engineers and researchers such as hydraulic analysis of microchannels and pool boiling heat transfer [21]. Conventional fluids have low capability of thermal transfer due to lack of thermal conductivity. Hence, an advanced heat transfer fluid called nanofluid was pioneered by Choi and Eastman [22] by disperse the nanoparticles in the base fluid. Later, the advanced in nanotechnology industry led to the innovation of thermal transfer fluid named hybrid nanofluid. The diffusion of two type of particles in the conventional fluid is discovered by many researchers because of its ability in enhancing the heat properties of nanofluid. The experiment on hybrid nanofluid were done by Turcu *et al*., [23] and Jana *et al*., [24] to observe its impact on the thermal conductivity. The production of hybrid nanofluid of Cu-Al_2O_3/H_2O by Suresh *et al*., [25] is done by thermochemical technique.

Hybrid nanofluid is implemented in many heat transfer usages, for instances improving the coolant performance in vehicle engines, microchips and nuclear power system, and delivery of nano-drug for medical treatment [26,27]. Many scientists have done the researches on hybrid nanofluid flow using various geometric models. The MHD flow of Cu-Al_2O_3/H_2O hybrid nanofluid across a porous stretched plate with suction impact is explored by Devi and Devi [28]. High concentration of nanoparticle volume fraction raises the heat transfer in the flow. Upreti *et al*., [29] studied the entropy generation of carbon nanotubes (CNTs) on hybrid nanofluid over rotating horizontal squeezed plates. The presence of joule dissipation, heat source/sink and radiative thermal flux were analysed. Waini *et al*., [30] examined the MHD hybrid nanofluid flow past a porous sensor of squeeze surface. The mixed convective squeeze of hybrid nanofluid flow and non-linear radiative heat transfer past two disks was analysed by Nisar *et al*., [31]. The magnetized ferroparticles is used in the base fluids of ethylene glycol and water. The MHD squeeze flow of hybrid nanoparticles of Fe_3O_4 and MoS_2 in the influence of heat sink/source is investigated by Salehi *et al*., [32]. The conventional fluids of ethylene glycol and water are considered. Khashi'ie *et al*., [33] explored the effects of suction/injection on MHD flow of hybrid Cu-Al_2O_3/H_2O nanofluid over the lower stretching squeezed surface. Wahid *et al*., [34] investigated the impacts of radiative thermal transfer on MHD hybrid nanofluid flow across a porous vertical surface. The squeezing flow and radiative thermal transfer of copper and alumina hybrid nanoparticles on water-based fluid with joule dissipation and variable viscosity was reviewed by Famakinwa *et al*., [35]. For Casson hybrid nanofluid, the magnetic flow at a stagnation points and thermal transfer across stretched plate was discovered by Alghamdi *et al*., [36]. Kamis *et al*., [37] examined the thermal transfer of the fluid across porous stretched surface with suction impact. Then, Jyothi *et al*., [38] investigated the squeeze flow of Casson hybrid nanofluid with heat sink/source and thermophoresis. Noor *et al*., [39] discovered the influences of chemical reaction and heat sink/source on squeeze MHD flow of sodium alginate-based Jeffrey hybrid nanofluid in porous medium with thermal radiation.

The studies of the double diffusion or thermal and mass transfer through fluid flow are important in many practical applications such as in the field of air pollution, disposal of nuclear waste and petroleum reservoirs [40]. It is discovered that the process of double diffusion is more complex caused by the driving potentials of thermal and mass fluxes occurs simultaneously. Soret effect or thermo-diffusion is a heat flux produced due to temperature gradient. Besides, Dufour effect or diffusion-thermo is a mass flux produced due to concentration gradient. Dufour and Soret terms are considered in the energy and concentration equations, respectively. In general, the impacts of Dufour and Soret are not measured because the order of magnitude is not significant based on Fourier and Fick's laws. However, the effects are discovered when the density of particles at fluid surface is lower than the ambient fluid [41]. The researches on the influences of Soret and Dufour on hybrid nanofluid flow are explored in various geometry. For Casson nanofluid, Rafique *et al*., [42] explored the numerical solution of MHD flow across a non-linear inclined plate with Soret and Dufour, radiation, Brownian, thermophoresis, and heat sink/source impacts. Bidemi and Ahamed [43] examined the effects of radiation, heat sink/source, and Dufour and Soret on unsteady magnetic flow through an inclined plate through porous medium using Buongiorno model. Sekhar *et al*., [44] discovered the MHD flow on inclined stretched surface in the presence of Brownian, radiation, heat sink/source, Soret and Dufour, and chemical reaction. Noor *et al*., [45] discussed the MHD squeeze Casson nanofluid flow for the presence of chemical reaction, porous medium, thermal radiation, and joule dissipation. Later, the prior study was extended by Noor *et al*., [46] by examining the heat sink and source in the Jeffrey flow. The prior work is continued by Noor *et al*., [47] for the study of thermal radiation and Dufour and Soret impacts on Jeffrey flow on squeezed plates. For Casson hybrid nanofluid, Hafeez *et al*., [48] studied the MHD flow through porous medium over a vertical melting surface with Dufour and Soret, Joule heating and viscous dissipation effects. Further, Reddy *et al*., [49] reported the influences of Soret and Dufour, thermal radiation and magnetic field on hybrid Al_2O_3-Cu based Ethylene glycol nanofluid across a moving thin needle. Deepika *et al*., [50] analysed the MHD mixed convection flow of Casson hybrid nanofluid on a porous stretching plate with Soret and Dufour, and heat source/sink impacts.

Based on literature review, several studies on the squeeze of nanofluid flow over two surfaces are discovered. The review highlights that limited study are conducted on the squeezing flow for Casson hybrid nanofluid. The thermal and mass transfer of squeezing flow of Casson hybrid nanofluid with the effects of magnetic, porosity, heat sink/source, Soret and Dufour are not discovered yet. Hence, the unsteady magnetohydrodynamics flow of Casson hybrid nanofluid through two squeezed surfaces in permeable medium is investigated in this study. The heat and mass transfer analysis with the influences of heat sink/source, chemical reaction and Soret and Dufour are observed. Copper and alumina are taken as hybrid nanoparticles with sodium alginate as the conventional fluid.

The potential application of this study is implemented for the modelling of fluid with hybrid nanoparticles as a coolant in the radiator. The large radiator is used to maximize the cooling effects on the engine, which cause high energy is required to maintain the system. Hence, the implementation of hybrid nanofluid is potentially useful in the modelling of small size of radiator and it has presented a good outcome in energy saving and emission reduction. Furthermore, the influence of magnetic field is examined in the flow. It is discovered that the conversion of kinetic energy of particles into a voltage enhances by applying magnetic field and plasma conductivity. The presence of chemical reaction in the mathematical model is to investigate the coolant in a nuclear reactor. It is used to remove heat from the nuclear reactor engine and transfer the heat to electrical generators and the environment.

The present study explores the following research questions

i. How do the mathematical models for MHD Casson hybrid nanofluid in the problem of unsteady squeezing flow through a porous medium can be formulated?
ii. How does the combined effects of heat sink/source, chemical reaction, and Soret and Dufour will affect the heat and mass transfer characteristics of the fluid flow?
iii. How to develop a programming code in MATLAB software to find the numerical solutions of the problems?

2. Mathematical Formulation

Consider the unsteady MHD flow of Casson hybrid nanofluid in permeable medium with chemical reaction, Soret and Dufour, and heat sink/source. The geometrical model presents the squeeze flow of Casson hybrid nanofluid across two surfaces. As illustrated in Figure 1, the length between two surfaces is $y = \pm h(t) = \pm l(1-\alpha t)^{\frac{1}{2}}$. The external force with velocity, $v_w(t) = \frac{\partial h(t)}{\partial t}$ is exerted on the both surfaces. It moves further when $\alpha < 0$ and moves closer when $\alpha > 0$ until $t = 1/\alpha$. The magnetic field is induced vertically at the lower surface, $B(t) = B_0(1-\alpha t)^{-1/2}$ [51]. The mixture of two type of hybrid nanoparticles, which are alumina and copper in the conventional fluid of Casson fluid are analysed.

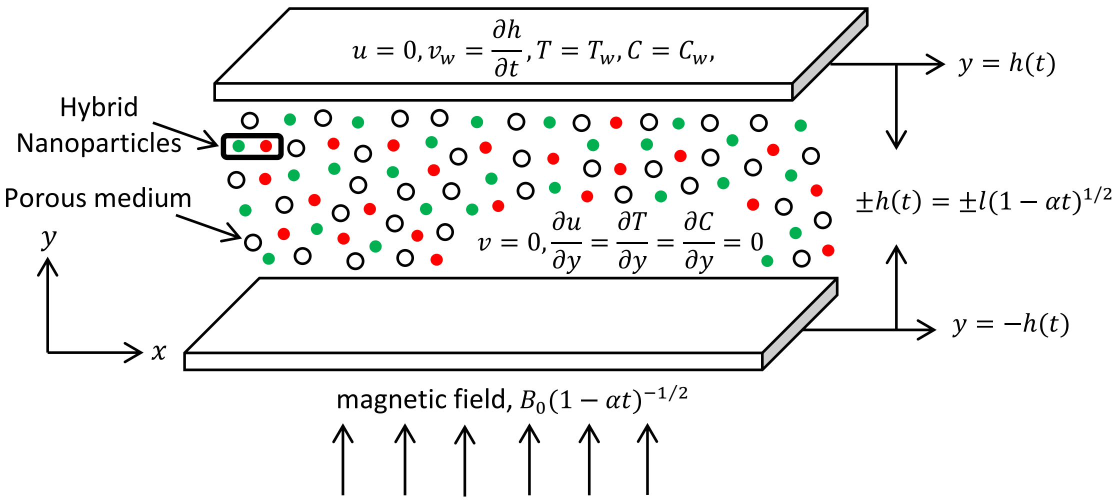

Fig 1. Geometry model of squeeze flow of hybrid nanofluid

Table 1 [52] and Table 2 [53] demonstrate the correlations on thermophysical properties and values for hybrid nanofluid.

Table 1
Correlations on thermophysical properties of hybrid nanofluid

Properties	Hybrid nanofluid
Dynamic viscosity (μ)	$\frac{\mu_{hnf}}{\mu_f} = \frac{1}{\left(1-\phi_{hnf}\right)^{2.5}}$
Density (ρ)	$\rho_{hnf} = \left(1-\phi_{hnf}\right)\rho_f + \phi_{Al_2O_3}\rho_{Al_2O_3} + \phi_{Cu}\rho_{Cu}$
Heat capacity $\left(\rho C_p\right)$	$\left(\rho C_p\right)_{hnf} = \left(1-\phi_{hnf}\right)\left(\rho C_p\right)_f + \phi_{Al_2O_3}\left(\rho C_p\right)_{Al_2O_3} + \phi_{Cu}\left(\rho C_p\right)_{Cu}$
Electrical conductivity (σ)	$\frac{\sigma_{hnf}}{\sigma_f} = \left[\frac{\left(\frac{\phi_{Al_2O_3}\sigma_{Al_2O_3}+\phi_{Cu}\sigma_{Cu}}{\phi_{hnf}}\right) + 2\sigma_f + 2\left(\phi_{Al_2O_3}\sigma_{Al_2O_3}+\phi_{Cu}\sigma_{Cu}\right) - 2\phi_{hnf}\sigma_f}{\left(\frac{\phi_{Al_2O_3}\sigma_{Al_2O_3}+\phi_{Cu}\sigma_{Cu}}{\phi_{hnf}}\right) + 2\sigma_f - \left(\phi_{Al_2O_3}\sigma_{Al_2O_3}+\phi_{Cu}\sigma_{Cu}\right) + \phi_{hnf}\sigma_f}\right]$
Thermal conductivity (k)	$\frac{k_{hnf}}{k_f} = \left[\frac{\left(\frac{\phi_{Al_2O_3}k_{Al_2O_3}+\phi_{Cu}k_{Cu}}{\phi_{hnf}}\right) + 2k_f + 2\left(\phi_{Al_2O_3}k_{Al_2O_3}+\phi_{Cu}k_{Cu}\right) - 2\phi_{hnf}k_f}{\left(\frac{\phi_{Al_2O_3}k_{Al_2O_3}+\phi_{Cu}k_{Cu}}{\phi_{hnf}}\right) + 2k_f - \left(\phi_{Al_2O_3}k_{Al_2O_3}+\phi_{Cu}k_{Cu}\right) + \phi_{hnf}k_f}\right]$

Table 2
Thermophysical values for the properties of nanoparticles and base fluid

Properties	Cu	Al_2O_3	Sodium alginate ($C_6H_9NaO_7$)
ρ	8933	3970	989
C_p	385	765	4175
σ	5.96×10^7	3.69×10^7	0.07
k	400	40	0.6367
Pr	$-$	$-$	6.5

The continuity, momentum, energy and concentration equations of Casson hybrid nanofluid based on the fluid flow at boundary region are [54].

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

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\mu_{hnf}}{\rho_{hnf}}\left(1+\frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} - \frac{\sigma_{hnf}B(t)^2}{\rho_{hnf}}u - \frac{\mu_{hnf}}{\rho_{hnf}}\left(1+\frac{1}{\beta}\right)\frac{\varphi}{k_1(t)}u, \tag{2}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{hnf}}{\left(\rho C_p\right)_{hnf}}\frac{\partial^2 T}{\partial y^2} + \frac{\mu_{hnf}}{\left(\rho C_p\right)_{hnf}}\left(1+\frac{1}{\beta}\right)\left[4\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2\right] \tag{3}$$
$$+ \frac{Q(t)}{\left(\rho C_p\right)_{hnf}}T + \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2},$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} - k_c(t)C. \tag{4}$$

The correlated boundary conditions are [54]

$$u = 0, v = v_w = \frac{\partial h(t)}{\partial t}, T = T_w, C = C_w, \text{at } y = h(t), \tag{5}$$

$$\frac{\partial u}{\partial y}=0, v=0, \frac{\partial T}{\partial y}=0, \frac{\partial C}{\partial y}=0, \text{ at } y=0. \tag{6}$$

The discretization of ordinary differential equations (ODEs) from partial differential equations (PDEs) are done by applying similarity variables as follows [55]

$$u=\frac{\alpha x}{2(1-\alpha t)}f'(\eta),\quad v=-\frac{\alpha l}{2\sqrt{(1-\alpha t)}}f(\eta),\quad \eta=\frac{y}{l\sqrt{(1-\alpha t)}}\ ,\quad \theta=\frac{T}{T_w},\quad \phi=\frac{C}{C_w}, \tag{7}$$

Substitute the similarity variables Eq. (7) into equations Eq. (2), Eq. (4) and Eq. (9), the non-dimensional ODE forms are

$$\frac{\mu_{hnf}}{\mu_f}\frac{\rho_f}{\rho_{hnf}}\left(1+\frac{1}{\beta}\right)f^{iv}-S(\eta f'''+3f''+f'f''-ff''')-\frac{\sigma_{hnf}}{\sigma_f}\frac{\rho_f}{\rho_{hnf}}Ha^2f''$$
$$-\frac{\mu_{hnf}}{\mu_f}\frac{\rho_f}{\rho_{hnf}}\left(1+\frac{1}{\beta}\right)\frac{1}{Da}f''=0, \tag{8}$$

$$\frac{(\rho C_p)_f}{(\rho C_p)_{hnf}}\frac{k_{hnf}}{k_f}\frac{1}{Pr}\theta''+S(f\theta'-\eta\theta')+\frac{(\rho C_p)_f}{(\rho C_p)_{hnf}}\gamma\theta$$
$$+\frac{\mu_{hnf}}{\mu_f}\frac{(\rho C_p)_f}{(\rho C_p)_{hnf}}Ec\left[\left(1+\frac{1}{\beta}\right)[(f'')^2+4\delta^2(f')^2]\right]+Du\phi''=0, \tag{9}$$

$$\frac{1}{Sc}\phi''+S(f\phi'-\eta\phi')+Sr\theta''-R\phi=0, \tag{10}$$

with the non-dimensional boundary conditions [56]

$$f(\eta)=1, f'(\eta)=0, \theta(\eta)=1, \phi(\eta)=1, \qquad \text{at } \eta=1. \tag{11}$$

$$f(\eta)=0, f''(\eta)=0, \theta'(\eta)=0,\ \phi'(\eta)=0 \qquad \text{at } \eta=0, \tag{12}$$

The physical terms in the dimensionless equations are denoted by [57]

$$S=\frac{\alpha l^2}{2\nu_f},\ Ha=lB_0\sqrt{\frac{\sigma}{\rho_f\nu_f}},\ Da=\frac{k_0}{\varphi l^2},\ \delta=\frac{l}{x}(1-\alpha t)^{1/2},\ Pr=\frac{\nu_f}{\alpha_f},\ Ec=\frac{\alpha^2x^2}{4C_pT_w(1-\alpha t)^2},$$
$$\gamma=\frac{Q_0l^2}{\nu_f(\rho C_p)_f},\ Du=\frac{D_mk_T}{c_sc_p\nu_f}\frac{C_w}{T_w},\quad Sr=\frac{D_mk_T}{T_m\nu_f}\frac{T_w}{C_w},\quad Sc=\frac{\nu_f}{D_m},\ R=\frac{ak_2l^2}{\nu_f}.$$

3. Numerical Procedure

The nonlinear ordinary differential Eq. (8) to Eq. (10) with associated boundary conditions Eq. (11) and Eq. (12) are solved numerically using implicit finite difference scheme known as Keller-box method. This method is an unconditionally stable and succeed in obtaining the accurate results. It is also recommended to be used in solving the nonlinear parabolic problems. The four steps involved to obtain the numerical results are as follows:

i. The ordinary differential equations are reduced to a system of first order equations.
ii. The first order system is discretized to obtain the equations in the finite difference form by using central difference scheme.
iii. The nonlinear equations are linearized using Newton's method and then written in matrix-vector form.
iv. Finally, the linear system can be solved via block tri-diagonal elimination technique.

4. Results and Discussion

The main objective of study is to examine the behaviour of velocity, temperature, and concentration of Casson hybrid nanofluid under the effects of S, Da, β, Ha, ϕ_2, Ec, Sr, Du, γ and R. The Keller box techniques is implemented to solve the similarity Eq. (8) to Eq. (10) with boundary conditions Eq. (11) and Eq. (12). The computation and graphical outputs are conducted using MATLAB software. The suitable step size, $\Delta\eta = 0.01$ and width of boundary layer, $\eta_\infty = 1$ is applied to attain the accurate and proper results. The computation in MATLAB is ended once the difference of previous and current outputs approaches to 0.00001 [58]. The results obtained using current technique is validated by comparing the values of wall shear stress with Naduvinamani and Shankar [41] and Jyothi *et al.*, [38] as displayed in Table 3.

Table 3
Numerical outputs of $-f''(1)$ for S with $\beta \to \infty$, $Da \to \infty$, $Ha = Ec = \delta = Sr = Du = \gamma = R = \phi_2 = 0$ and $Sc = Pr = 1$

$-f''(1)$			
S	Naduvinamani and Shankar [39]	Jyothi *et al.*, [36]	Present outputs
−1.0	2.170090	2.170090	2.170255
−0.5	2.617403	2.617403	2.617512
0.01	3.007133	3.007133	3.007208
0.5	3.336449	3.336449	3.336504
2.0	4.167389	4.167389	4.167412

The graphical outputs under the effects of S, β, Ha, Da and ϕ_2 on velocity of fluid are presented in Figure 2 to 6. It is noteworthy that squeeze number, S indicates the motion of two plates. For $S > 0$, both plates move nearer one another, while the plates moves away when $S < 0$. The fluid velocity decelerating nearby lower plates, $\eta < 0.45$, whereas it accelerating in the area at middle plates, $\eta \geq 0.45$ for $S > 0$ as displayed in Figure 2. In contrary, the velocity increasing at $\eta < 0.45$, while it declining at $\eta \geq 0.45$ when $S < 0$. According to the behaviour of fluid velocity, the fluid flow across the medium at the faster rate caused by compressing of both plates. Meanwhile, the velocity declining due to high resistance in the broader channel encountered by the flow.

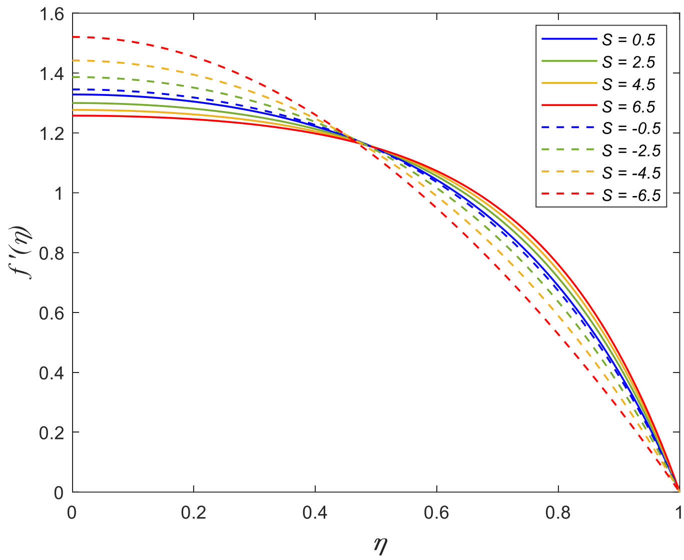

Fig. 2. Influences of S on $f'(\eta)$

Figure 3 shows the velocity slowing down when $\eta \leq 0.5$, and it elevating when $\eta > 0.5$ for increment of β. The intermolecular forces within nanoparticles strengthen with the presence of β, which resulting the velocity decelerates nearby the lower plate.

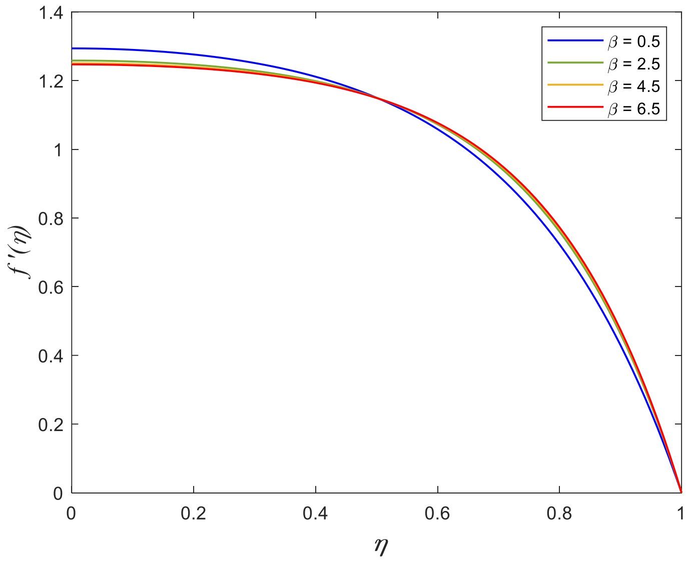

Fig. 3. Influences of β on $f'(\eta)$

Figure 4 depicts the velocity decreases when $\eta \leq 0.5$, whereas it raises when $\eta > 0.5$ with boost in Ha. The induction of magnetic field on the lower plate result in the fluid velocity decelerates due to resistance on the flow boost with the impact of Lorentz force.

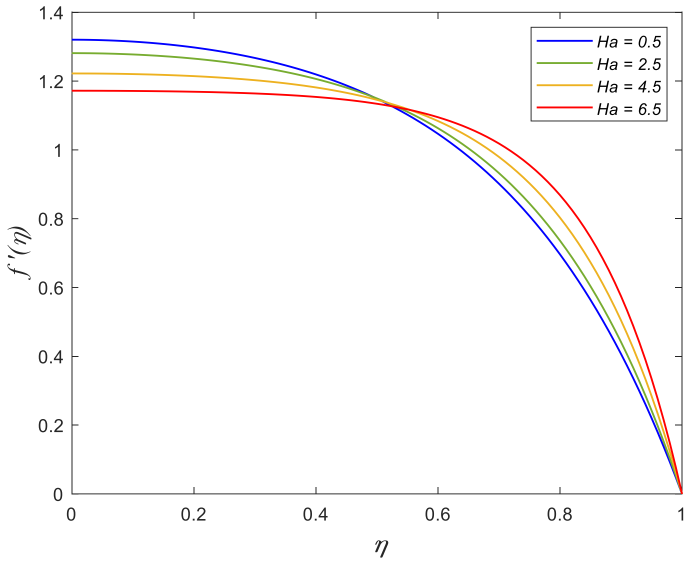

Fig. 4. Influences of Ha on $f'(\eta)$

Figure 5 portrays the velocity rising when $\eta \leq 0.5$, while it slowing down at $\eta > 0.5$ for rises Da. The enhancement of Darcy number enhances the permeability of medium, which lead to increase the fluid flow through the medium.

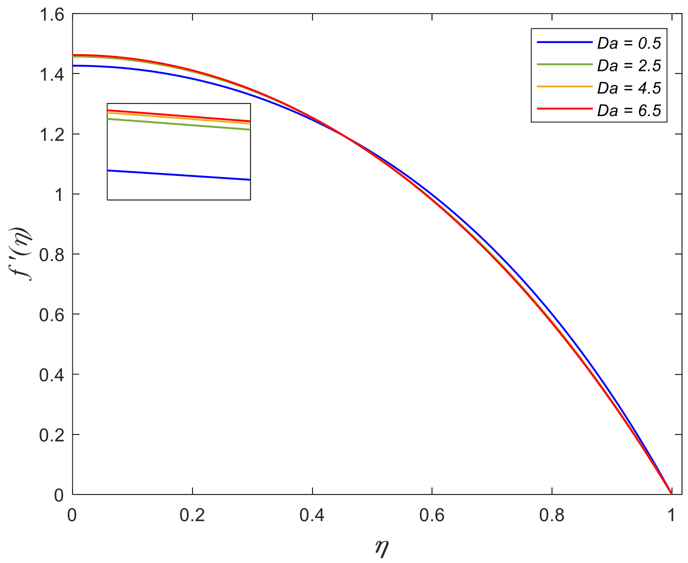

Fig. 5. Influences of Da on $f'(\eta)$

The velocity enhances when $\eta \leq 0.5$ and it dropping when $\eta > 0.5$ for rising ϕ_2 as shown in Figure 6. The velocity reduces in the middle of channel with addition of nanoparticles. It is discovered that the fluid cannot flow rapidly due to the stronger collision of fluid particles and nanoparticles.

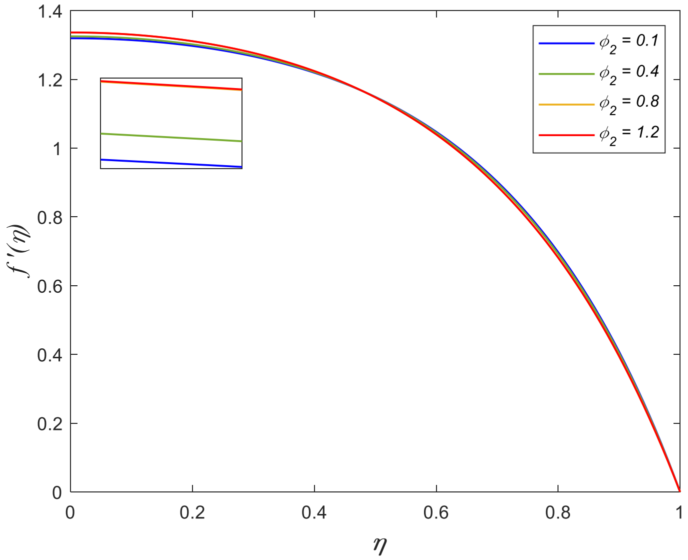

Fig. 6. Influences of ϕ_2 on $f'(\eta)$

Figure 7 to 11 depicts the impacts of Ec, γ, ϕ_2, Sr and Du on fluid temperature. The temperature in Figure 7 increases as Ec rises. It implies kinetic energy and heat induced by the motion of nanoparticles in fluid enhances for elevates Ec.

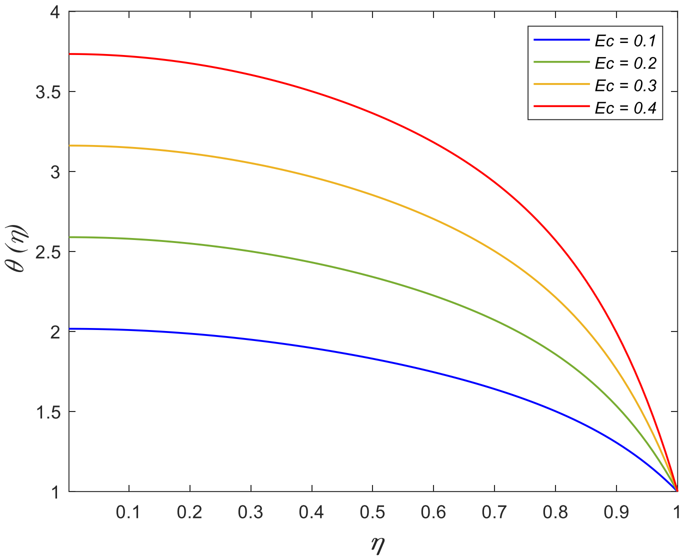

Fig. 7. Influences of Ec on $\theta(\eta)$

Figure 8 demonstrates the temperature drops with enhance in heat absorption $(\gamma < 0)$, while it elevates for rising the heat generation $(\gamma > 0)$. The transfer of heat energy from fluid to the plates increasing, which causing the fluid temperature decreases. Meanwhile, the heat sink raises the thermal energy in the fluid and thus, enhancing the temperature of fluid.

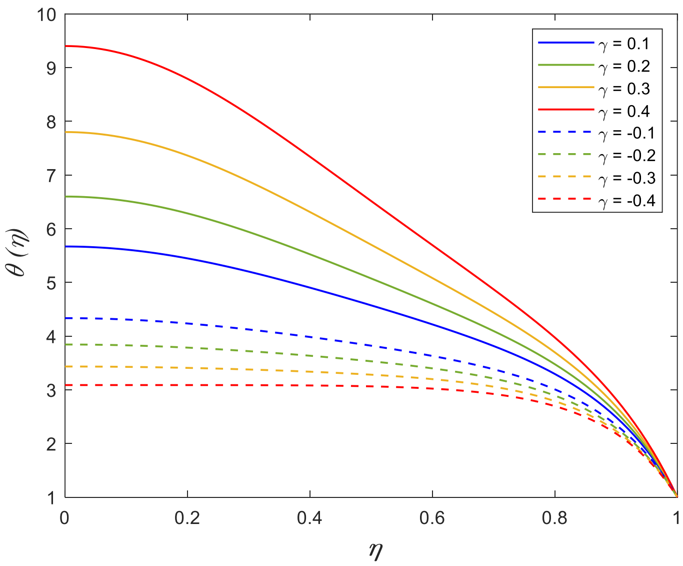

Fig. 8. Influences of γ on $\theta(\eta)$

Figure 9 presents the deceleration of temperature when ϕ_2 elevates because the volume fraction of nanoparticles promotes the fluid thermal conductivity. Therefore, the rate of thermal transfer from the fluid to surfaces enhances, which result in dropping of fluid temperature.

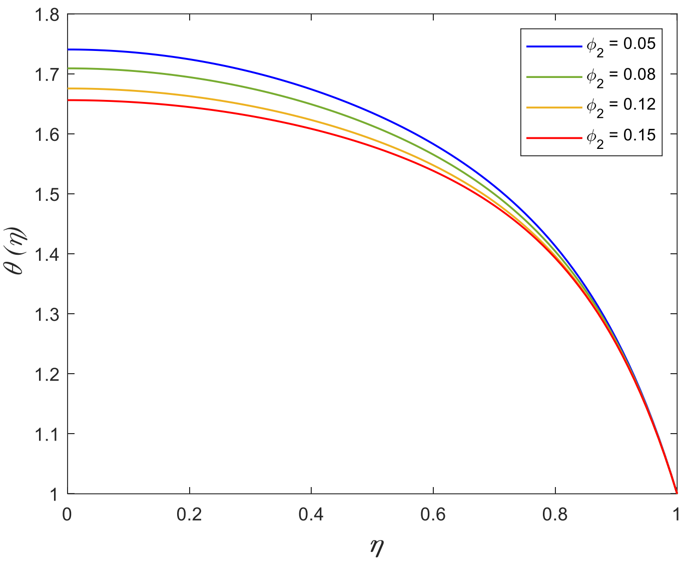

Fig. 9. Influences of ϕ_2 on $\theta(\eta)$

Figure 10 illustrates the temperature in the flow boosts for increasing Sr. Soret number is inverse proportional to the kinematics viscosity. It indicates that the increment of Sr reduce the viscosity in the flow region, which weaken the resistance encountered in the fluid. Hence, it accelerating the kinetic energy of nanoparticles and increase the fluid temperature.

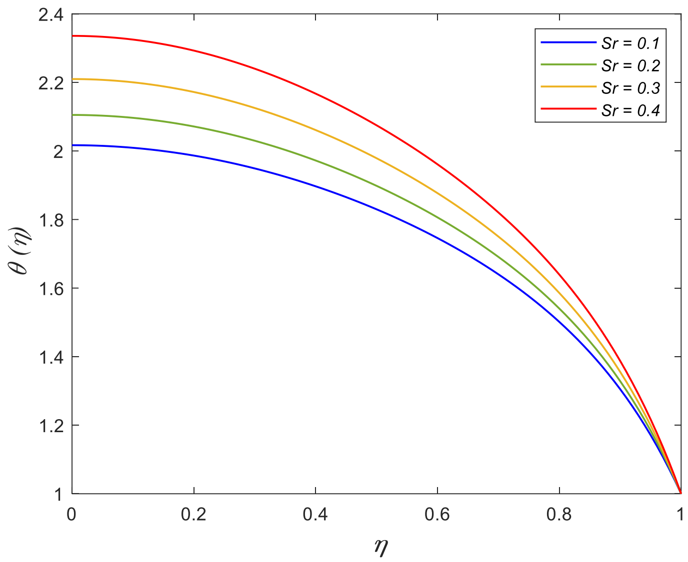

Fig. 10. Influences of Sr on $\theta(\eta)$

Figure 11 discovers the temperature boosts when Du rises because the kinematic viscosity in the flow drops, which resulting the resistance decrease and kinetic energy of particles elevates in the fluid.

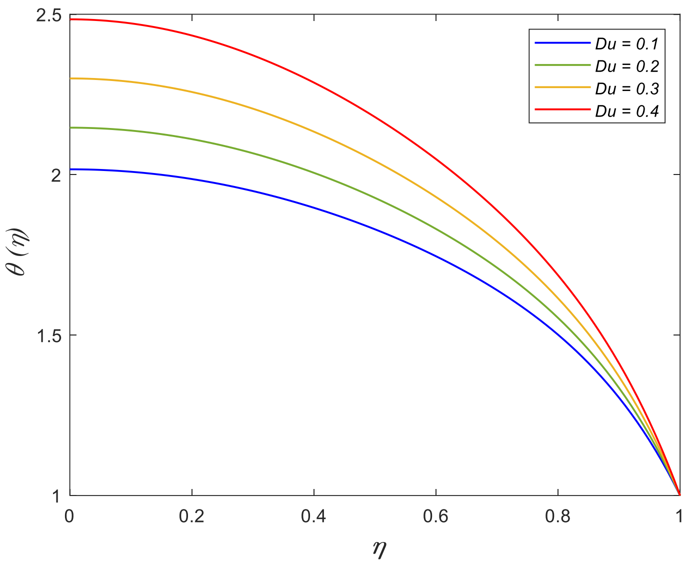

Fig. 11. Influences of Du on $\theta(\eta)$

The influences of Sr, Du, ϕ_2 and R on concentration are shown in Figures 12 to 15. The concentration reduces as observed in Figure 12 for increasing Sr. It is noticed that the transfer of mass in the fluid to the upper surface rises due to the presence of thermal diffusion or Soret effect.

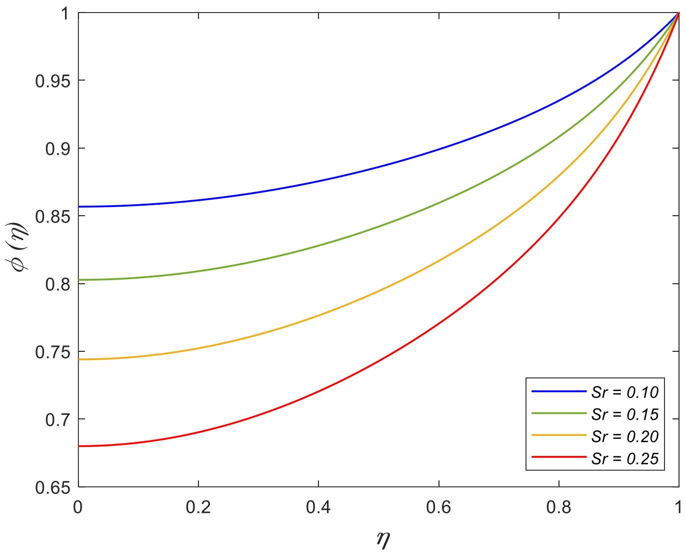

Fig. 12. Influences of Sr on $\phi(\eta)$

Figure 13 portrays the concentration declines with elevate in Du. The generation of energy flux caused by concentration differences enhances result from the effect of Dufour parameter. It has caused the fluid concentration drops due to the increment of temperature in the flow region.

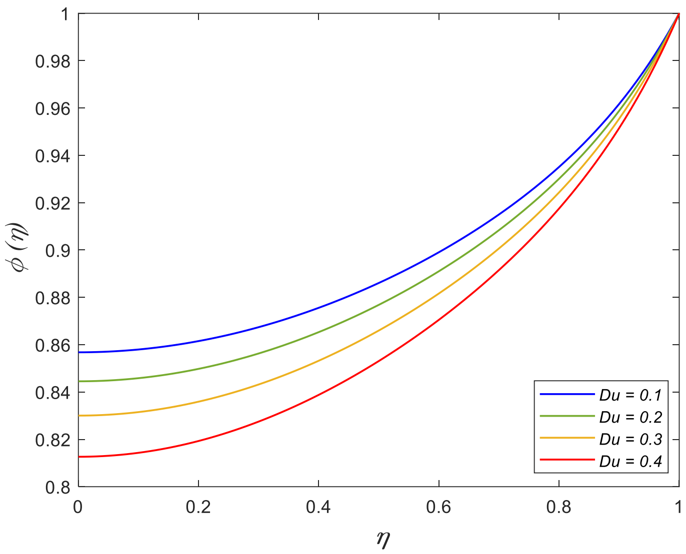

Fig. 13. Influences of Du on $\phi(\eta)$

Figure 14 shows the concentration increasing when ϕ_2 elevates due to the fluid viscosity escalates with high volume fraction of nanoparticles.

Figure 15 displays the decrease in concentration for destructive chemical reaction, $R > 0$, while it enhancing for constructive chemical reaction, $R < 0$. The increment of constructive reaction promotes the chemical reaction rate, whereas adverse effect is examined in destructive reaction.

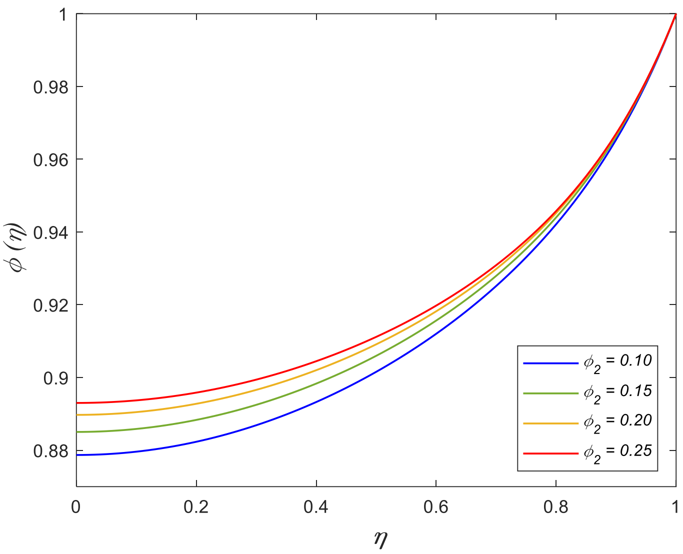

Fig. 14. Influences of ϕ_2 on $\phi(\eta)$

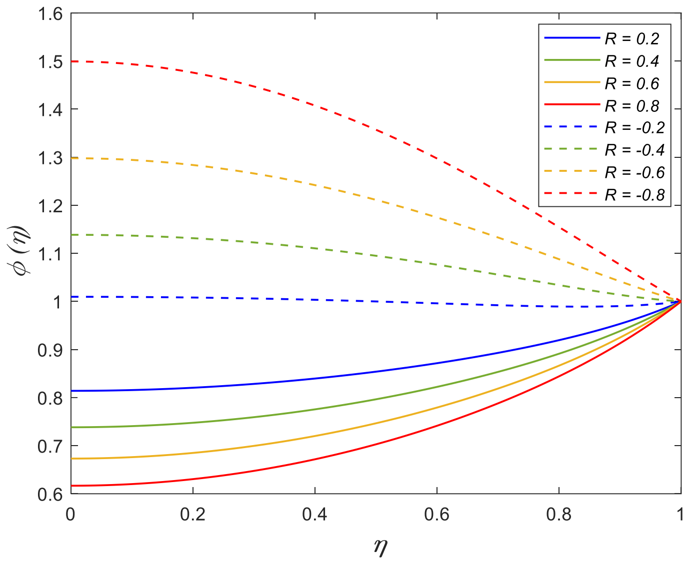

Fig. 15. Influences of R on $\phi(\eta)$

The effects of Ha and Da on wall shear stress are illustrated in Figure 16. The skin friction increasing when Ha boosts, while it declining as Da rises. It is caused by the Lorentz force in flow escalates with raise in Ha and therefore, it enhances the friction force close to the plates. In contrast, the flow moving rapidly close to the plate for increasing the permeability of medium. Hence, the skin friction at the boundary area decelerates due to the friction force in the flow decreases.

Figure 17 illustrates the increment of Nusselt number when Du and γ elevates. The ratio of convective and conductive thermal transfer is denoted by Nusselt number. The fluid temperature escalates because the generation of heat flux boost with higher Du and γ values. It indicates that the thermal convection is greater than conduction, which lead to the convective thermal transfer and Nusselt number increases.

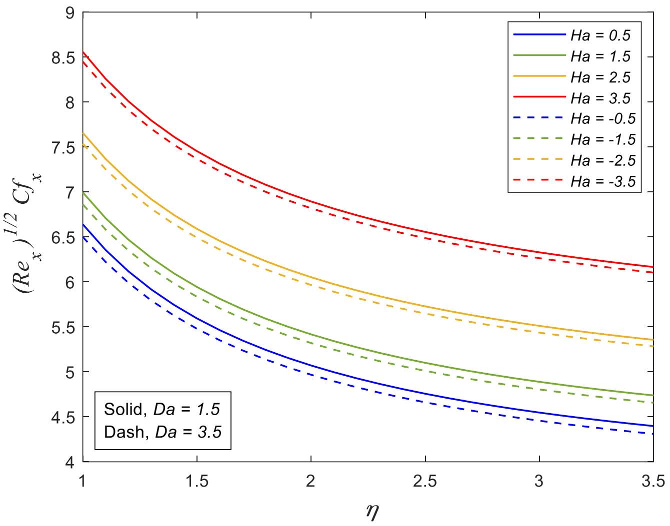

Fig. 16. Effect of Ha and Da on $(Re_x)^{1/2}Cf_x$

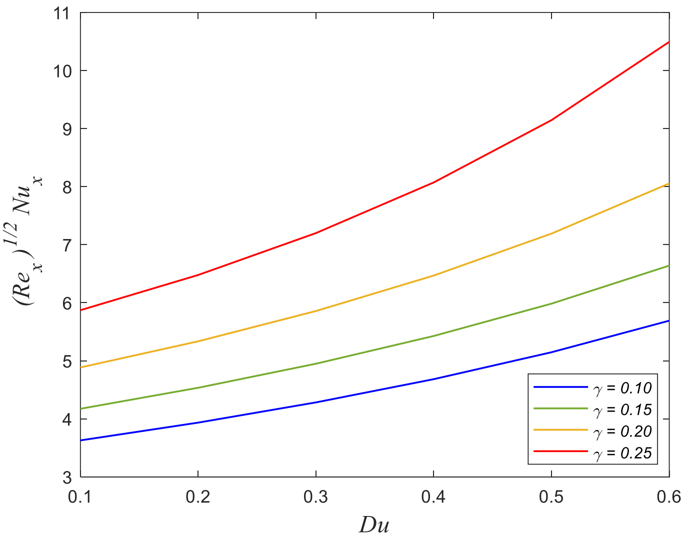

Fig. 17. Effect of Du and γ on $(Re_x)^{1/2}Nu_x$

Figure 18 shows the Sherwood number increases for $R > 0$ and it decreasing for $R < 0$. Sherwood number is the ratio of convection and diffusion mass transfer. The constructive reaction $(R < 0)$ promotes the fluid concentration, which result in the diffusive mass transfer increasing. Hence, it indicates that the convective mass transfer and Sherwood number drops in the flow. The contrary behaviour is noticed on destructive chemical reaction $(R > 0)$ caused by low fluid concentration. Consequently, the Sherwood number increases due to the convective mass transfer in fluid more dominant. Furthermore, the Sherwood number elevates with raise in Sr. The reduction of fluid concentration in Figure 12 highlights that the diffusive mass transfer drops when Sr increases. Sherwood number is inversely proportional to mass transfer by diffusion. Thus, it concludes that the increase in Sr promotes the convective mass transfer and boosts the Sherwood number in the fluid flow.

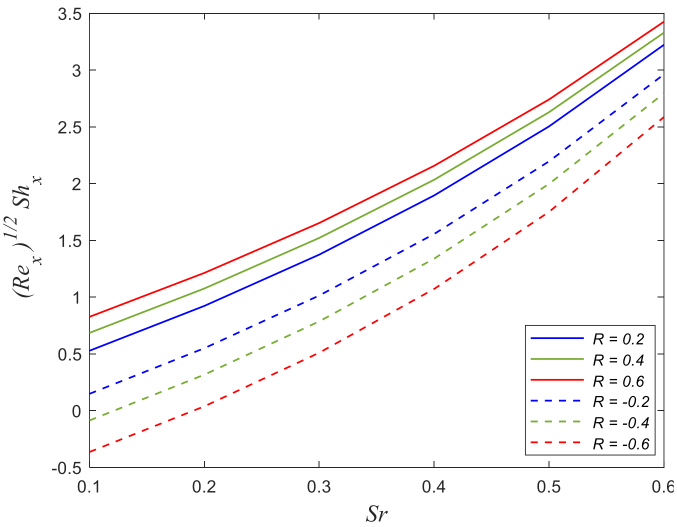

Fig. 18. Effect of Sr and R on $(Re_x)^{1/2}Sh_x$.

4. Conclusions

In this study, the impacts of Soret and Dufour on squeezing MHD flow Casson hybrid nanofluid through permeable medium with heat sink/source and chemical reaction was analysed. The resulting equations are discretized using Keller-box technique by developing the algorithm in MATLAB. The present outputs are compared with prior outputs from selected papers and shown in good agreement. The physical behaviours and quantities of the flow were affected by different values of S, Da, β, Ha, ϕ_2, Ec, Sr, Du, γ and R. The main results of Casson hybrid nanofluid according to the discussions are concluded as

i. The acceleration of axial velocity occurs when the surfaces is squeezing $(S > 0)$ and it decelerating when the surfaces is separating $(S < 0)$ near the upper plate.
ii. The velocity of fluid decreasing in the middle of channel as β and Ha elevates, and it increasing when Da and ϕ_2 rises.
iii. The wall shear stress escalates for rises of Ha, while it reduces for enhancing Da.
iv. The heat transfer rate and temperature of fluid boosts as Ec, γ and Du increases, and the contrary behaviour is shown for enhancing ϕ_2.
v. The fluid concentration declines and the mass transfer rate enhances with elevate in Sr.
vi. The fluid concentration elevates, while the convective mass transfer declining when $R < 0$. The adverse behaviour of fluid is observed for $R > 0$.

For future works, it is recommended to further this study by investigating the ternary hybrid nanofluid in the flow. The importance of ternary nanoparticles is acknowledged as it improves the thermal performance of nanofluid at low cost. The implementation of ternary hybrid nanofluid as a coolant in thermal based devices is important because it has result in energy saving and emission reduction.

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