Fluid Dynamics &
Materials Processing

Tech Science Press

DOI: 10.32604/fdmp.2022.021996

ARTICLE

Impact of Radiation and Slip on Newtonian Liquid Flow Past a Porous Stretching/Shrinking Sheet in the Presence of Carbon Nanotubes

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Received: 16 February 2022 Accepted: 29 March 2022

ABSTRACT

The impacts of radiation, mass transpiration, and volume fraction of carbon nanotubes on the flow of a Newtonian fluid past a porous stretching/shrinking sheet are investigated. For this purpose, three types of base liquids are considered, namely, water, ethylene glycol and engine oil. Moreover, single and multi-wall carbon nanotubes are examined in the analysis. The overall physical problem is modeled using a system of highly nonlinear partial differential equations, which are then converted into highly nonlinear third order ordinary differential equations via a suitable similarity transformation. These equations are solved analytically along with the corresponding boundary conditions. It is found that the carbon nanotubes can significantly improve the heat transfer process. Their potential application in cutting-edge areas is also discussed to a certain extent.

KEYWORDS

Carbon nanotubes; porous media; newtonian fluid; radiation

Nomenclature

a	constant
b	constant
A, B	first and second order slip parameters
Bi	Biot number
C	constant
d	stretching/shrinking sheet parameter
Da^{-1}	inverse Darcy number
K_1	thermal slip
K_P	permeability
f	similarity variable
Rd	radiation parameter
Pr	Prandtl number
q_0	constant

f_0	mass transpiration parameter
T	temperature
T_w	wall temperature
T_∞	free stream temperature
v_w	wall mass transfer velocity

Greek Symbols

η	similarity variable
γ_1 , γ_2	first and second order slips
θ	similarity variable for temperature
ϕ	solid volume fraction

Subscript

CNT	parameter for carbon nanotubes
f	parameter of base fluid
MWCNT	multi wall carbon nanotubes
SWCNT	single wall carbon nanotubes

Abbreviations

BC	boundary conditions
ODE	ordinary differential equation
PDE	partial differential equation

1 Introduction

The fluid flow with carbon nanotubes (CNTs) through porous media considering the mass transpiration is an important concept in the field of industry and medicine, especially in nano-medicine. The porous media approach is useful in the treatment of cancer tumors as the tumor growth is represented by the mathematical model where the mass transfer represents the process of growth and death. The model of tumor growth represented by the porous media approach studied in detail by Shelton [1]. In 2014, Sunil et al. [2] solved the system of fractional differential equation by using the homotopy analysis method and Laplace transform method and obtain the convergence series. Bhattacharya [3] studied the first order homogeneous chemical reaction with the impact of mass transfer by using shooting method. The influence of viscous dissipation and chemical reaction on the stagnation point flow of NF over the stretching/shrinking plate was studied by Murthy et al. [4]. Talay et al. [5] investigated the chemical reaction of non-Newtonian fluid through porous medium to obtain exact solution and some interesting properties that leads to further study on chemically reactive species.

Fazle et al. [6] studied the unsteady flow with velocity, thermal and solutal slips further obtain the numerical solution. The Newtonian fluid flow due to superlinear stretching sheet is investigated by Siddheshwar et al. [7]. Mahabaleshwar et al. [8–11] studied the impact of slip and radiation on the flow of Walters' B liquid over linearly stretching plate embedded in porous media and got the analytical solution for different fluids with the presence of different parameters. Siddheshwar et al. [12] approached the new analytical solution procedure for both Newtonian and non-Newtonian fluid flow due to linear stretching sheet using the technique of perturbation and obtain the analytical solution for velocity and stream function. Mahabaleshwar et al. [13] modeled the problem of axisymmetric flow over stretching sheet in the presence slip which does not have exact analytical solution leads to obtain solution by suing differential transform method and Pade approximation. Some authors use Laplace transformation (LT) to get the analytical solution for the flow and heat transfer of CNTs and nanofluids with the presence of different parameters. Abdelhalim et al. [14] studied in the presence of magnetic field and obtain new analytical solution. Hoda et al. [15] investigated on the medical application, mainly on cancer tumor treatment of it with convective condition and gives some numerical results. Malkeet et al. [16] gave the detailed applications and properties of Laplace transformation. Mahabaleshwar et al. [17] made the contribution on the inclined MHD flow, mass and heat transfer with radiation effect. Mahabaleshwar et al. [18] investigated the MHD flow with carbon nanotubes by considering the effect of mass transpiration and radiation on it. Anusha et al. [19,20] examined the unsteady inclined MHD flow for Casson fluid with hybrid nanoparticles and due to porous media, respectively. Sneha et al. [21] investigated the flow and heat transfer of dusty fluid for its analytical solution.

Hamad [22] studied on natural convection flow and found the analytical solution for the MHD flow by adding NF. Andersson et al. [23] investigated the incompressible flow with the consequence of transverse MHD due to stretching sheet by using the power law model. Andersson et al. [24] first time gave the work on concentration distribution with the impact of higher order chemical reaction for the linearly stretching sheet and found numerical solution for momentum and concentration. Paul et al. [25] considered the hydrodynamic flow and a body is located in it from which a chemically reactive species is emitted and he consider the two reaction types viz, reactant is destroyed in one reaction type and it is generated in another.

The intend of the current examination is to analyze the influences of radiation and mass transpiration with porous media on the flow of CNTs due to stretching/shrinking plate with the existence of Navier's slip and physical model is as shown in Fig. 1. Further to obtain the analytic solution for velocity profile and temperature field.

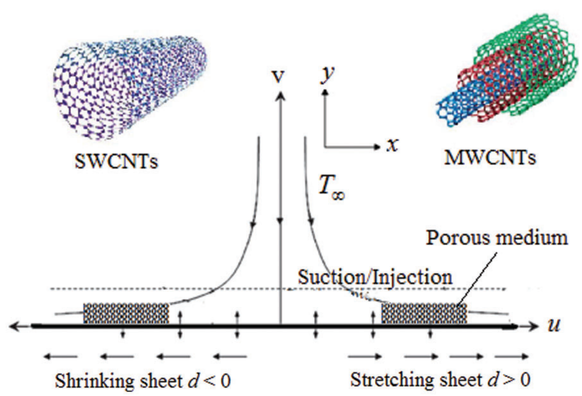

Figure 1: Schematic diagram of the flow problem

2 Equations and Mathematical Expressions

The steady 2-D flow and heat transfer of electrically conducting fluid due to stretching/shrinking sheet in porous media with permeability K is considered in the presence of mass transpiration and radiation. The flow is along x-axis and y is perpendicular to it. The wall temperature is maintained constant at T_w and T_∞ is the ambient temperature. The fluids considered are base liquids like water, ethylene glycol and engine oil with single and multi-walled carbon nanotubes. The governing equations for described momentum and energy conservations are as follows:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=v_{nf}\frac{\partial^2 u}{\partial y^2}-\frac{v_{nf}}{K}u, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_{nf}}{(\rho C_P)_{nf}}\frac{\partial^2 T}{\partial y^2}-\frac{1}{(\rho C_P)_{nf}}\frac{\partial q_r}{\partial y}, \tag{3}$$

with B.Cs as

$$u=dax+A\frac{\partial u}{\partial y}+B\frac{\partial^2 u}{\partial y^2}\ ,\quad \mathrm{v}=\mathrm{v}_w\ ,\quad -k_f\frac{\partial T}{\partial y}=h(T_w-T)\quad \text{at } y=0,$$

$$u\to 0\ ,\quad T\to T_\infty\quad \text{as}\quad y\to\infty, \tag{4}$$

where, $q_r=-\frac{16\sigma^* T_\infty^3}{3\kappa^*}\frac{\partial^2 T}{\partial y^2}$ is the radiative heat flux and all parameters are as mentioned in nomenclature. On considering the suitable similarity transformation giving velocity component,

$$u=cx\frac{\partial F}{\partial \eta}\quad ,\quad \mathrm{v}=-\sqrt{cv_f}F(\eta)\quad ,\quad \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}\quad \text{with}\quad \eta=\sqrt{\frac{c}{v_f}}y, \tag{5}$$

and

$$\frac{1}{\beta_1}=\frac{\mu_{hnf}}{\mu_f}=\frac{1}{(1-\phi_1)^{2.5}}, \tag{6a}$$

$$\beta_2=\frac{\rho_{hnf}}{\rho_f}=(1-\phi)+\phi\left(\frac{\rho_{CNT}}{\rho_f}\right), \tag{6b}$$

this gives, $v_{nf}=\frac{v_f}{\beta_1\beta_2}$,

$$\beta_3=\frac{(\rho C_P)_{nf}}{(\rho C_P)_f}=(1-\phi)+\phi\frac{(\rho C_p)_{CNT}}{(\rho C_P)_f}, \tag{6c}$$

$$\beta_4=\frac{k_{nf}}{k_f}=\frac{k_{CNT}+2k_f+2\phi(k_{CNT}-k_f)}{k_{CNT}+2k_f-\phi(k_{CNT}-k_f)}, \tag{6d}$$

On applying (5) and (6a) to (6d) in (2) and (3) gives,

$$\frac{1}{\beta_1\beta_2}\frac{\partial^3 F}{\partial \eta^3}+F\frac{\partial^2 F}{\partial \eta^2}-\left(\frac{\partial F}{\partial \eta}\right)^2-\frac{1}{\beta_2}Da^{-1}\frac{\partial F}{\partial \eta}=0, \tag{7a}$$

$$\frac{\beta_4}{\beta_3}\left(1+\frac{4}{3}Rd\right)\frac{\partial^2\theta}{\partial \eta^2}+PrF(\eta)\frac{\partial\theta}{\partial \eta}=0, \tag{7b}$$

and B.Cs reduces to,

$$F(0)=S\ ,\quad \left(\frac{\partial F}{\partial \eta}\right)_{\eta=0}=d+\gamma_1\left(\frac{\partial^2 F}{\partial \eta^2}\right)_{\eta=0}+\gamma_2\left(\frac{\partial^3 F}{\partial \eta^3}\right)_{\eta=0},\quad \left(\frac{\partial F}{\partial \eta}\right)_{\eta\to\infty}=0,$$

$$\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}=-Bi[1-\theta(0)]\ ,\quad \theta(\infty)=0. \tag{7c}$$

Here, $Da^{-1}=\frac{v_f}{Kc}$ is the inverse Darcy number,

$Rd = \frac{4\sigma^* T_\infty^3}{\kappa^* k_{nf}}$ is the radiation parameter,

$\gamma_1 = A\sqrt{\frac{c}{v_f}}$ and $\gamma_2 = B\frac{c}{v_f}$ are first and second order slips respectively (see Mahantesh et al. [26], Lin [27]),

$Bi = \frac{h}{k_f}\sqrt{\frac{v_f}{c}}$ is the Biot number.

Take $\beta = \beta_1\beta_2$ and use the function transformation as, $F(\eta) = \frac{1}{\sqrt{\beta}}f(\xi),\ \ \theta(\eta) = \phi(\xi),\ \ \xi = \sqrt{\beta}\eta,$

$$\frac{\partial^3 f}{\partial\eta^3} + f\frac{\partial^2 f}{\partial\eta^2} - \left(\frac{\partial f}{\partial\eta}\right)^2 - K_P\frac{\partial f}{\partial\eta} = 0, \tag{8a}$$

$$\left(1 + \frac{4}{3}Rd\right)\frac{\partial^2\phi}{\partial\xi^2} + Pr^* f(\xi)\frac{\partial\phi}{\partial\xi} = 0, \tag{8b}$$

here,

$K_P = \frac{Da^{-1}}{\beta_2}$ and $Pr^* = \frac{Pr\beta_3}{c\beta_4}$.

By taking the substitutions $\gamma_1\sqrt{\beta} = \chi_1,\ \ \gamma_2\sqrt{\beta} = \chi_2,\ \ S\sqrt{\beta} = f_0,\ \ \frac{Bi}{\sqrt{\beta}} = K_1$, the reduced B.Cs are,

$$f(0) = f_0,,\quad \left(\frac{\partial F}{\partial\eta}\right)_{\eta=0} = d + \chi_1\left(\frac{\partial^2 f}{\partial\xi^2}\right)_{\xi=0} + \chi_2\left(\frac{\partial^3 f}{\partial\xi^3}\right)_{\xi=0},\quad \left(\frac{\partial f}{\partial\xi}\right)_{\xi\to\infty} = 0, \tag{8c}$$

$$\left(\frac{\partial\phi}{\partial\xi}\right)_{\xi=0} = -K_1[1 - \phi(0)],\quad \phi(\infty) = 0. \tag{8d}$$

2.1 Solution of Momentum Problem

The exact analytical solution of Eq. (8a) as in Turkyilmazoglu [28] is as,

$$f(\xi) = f_0 + \frac{d(1 - exp[-\alpha\xi])}{\alpha(1 + \chi_1\alpha - \chi_2\alpha^2)}, \tag{9}$$

This gives the velocity as,

$$\frac{\partial f}{\partial\xi} = \frac{d exp[-\alpha\xi]}{1 + \chi_1\alpha - \chi_2\alpha^2}, \tag{10}$$

Using this in (8a) gives the relation,

$$\chi_2\alpha^4 - (\chi_1 + f_0\chi_2)\alpha^3 - (1 - f_0\chi_1 + K_P\chi_2)\alpha^2 + (f_0 + K_P\chi_1)\alpha + (d + K_P) = 0, \tag{11}$$

From this equation the exponent α can be obtained.

2.2 Solution of Energy Problem

The exact solution of Eq. (8b) can be found by using the new variable $t = \frac{Pr^*}{\alpha^2}exp[-\alpha\xi]$ and gives,

$$Rt\frac{\partial^2\phi}{\partial t^2} + (R - \varepsilon_2 + \varepsilon_1 t)\frac{\partial\phi}{\partial t} = 0 \tag{12}$$

here
$R = 1 + \frac{4}{3}Rd,\ \varepsilon_1 = \frac{d}{1 + \chi_1\alpha - \chi_2\alpha^2},\ \varepsilon_2 = \frac{Pr^*[d + f_0\alpha(1 + \chi_1\alpha - \chi_2\alpha^2)]}{\alpha^2(1 + \chi_1\alpha - \chi_2\alpha^2)}$ are dummy variables.

The solution of Eq. (12) using the B.Cs (8d) is in the form of incomplete gamma function is as below:

$$\phi(t) = \frac{K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1}{R}t\right]\right\}}{\alpha\left(\frac{Pr^*}{\alpha^2}\right)^{\varepsilon_2/R}\left(\frac{\varepsilon_1}{R}\right)^{\varepsilon_2/R} + K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1 Pr^*}{R\alpha^2}\right]\right\}}, \tag{13a}$$

ϕ in terms of ξ becomes,

$$\phi(\xi) = \frac{K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1}{R}\frac{Pr^*}{\alpha^2}e^{-\alpha\xi}\right]\right\}}{\alpha\left(\frac{Pr^*}{\alpha^2}\right)^{\varepsilon_2/R}\left(\frac{\varepsilon_1}{R}\right)^{\varepsilon_2/R} + K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1 Pr^*}{R\alpha^2}\right]\right\}}, \tag{13b}$$

Then the temperature distribution will becomes,

$$\theta(\eta) = \frac{K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1}{R}\frac{Pr^*}{\alpha^2}exp\left[-\alpha\sqrt{\beta}\eta\right]\right]\right\}}{\alpha\left(\frac{Pr^*}{\alpha^2}\right)^{\varepsilon_2/R}\left(\frac{\varepsilon_1}{R}\right)^{\varepsilon_2/R} + K_1 exp\left(\frac{\varepsilon_1 Pr^*}{R\alpha^2}\right)\left\{\Gamma\left[\frac{\varepsilon_2}{R},\ 0\right] - \Gamma\left[\frac{\varepsilon_2}{R},\ \frac{\varepsilon_1 Pr^*}{R\alpha^2}\right]\right\}}, \tag{14}$$

The scaled Nusselt number is given by, $Nu = -\left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=0}$.

3 Figures and Discussions

The influence of mass transpiration, Navier's slip and thermal slips on the flow of incompressible viscous MWCNT/SWCNT is investigated. The system of PDEs is changed to system of nonlinear ODEs with constant coefficients by using the suitable similarity transformations for velocity and temperature. Then the analytical solution for velocity profile is obtained in exponential form and that for the temperature field was obtained in terms of incomplete gamma function. The concerned effects are analyzed by the help of different graphs for MWCNT/SWCNT. The model is shown for the flow over porous medium and the advantages of using porous medium for its applications in industry and medicine field. To study the effects of different base fluids for MWCNT and SWCNT, the different graphs are shown here.

In Fig. 2 the effect of solid volume fraction on $\sqrt{\beta}$ is plotted for all mentioned base fluids shown that SWCNT is more effected by ϕ than MWCNT. Among the base fluids engine oil is more effected and ethylene glycol has less effected by ϕ. Figs. 3 and 4 demonstrate the behaviour of skin friction verses mass transpiration for different values of permeability parameter by taking different roots. Fig. 5 is the plot for skin friction verses mass transpiration for different values of first order slip. Further in Fig. 6 the effect of ϕ on Pr as in Eq. (15) is studied for mentioned base fluids. And shown that water has less Pr value and engine oil has highest Pr value. Pr value of SWCNTs is more than that of MWCNTs.

To study the variation of skin friction with mass transpiration f_0 is studied for different conditions and for different roots values of Eq. (11).

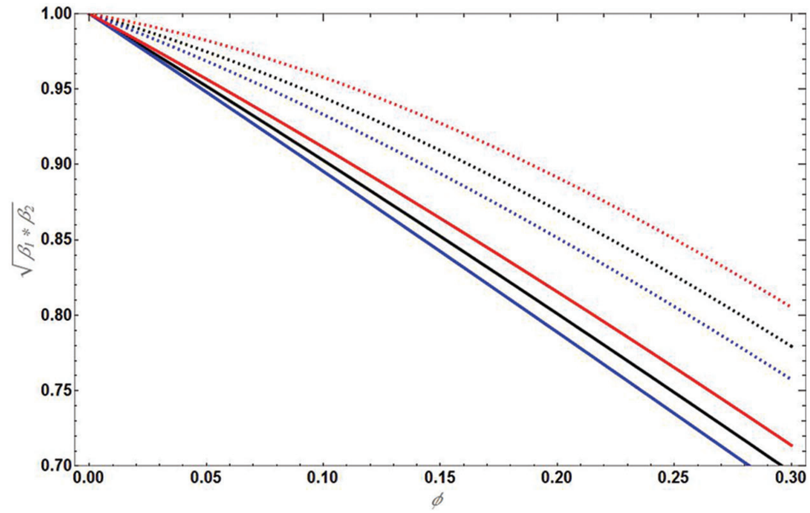

Figure 2: The plot showing the values $\sqrt{\beta}$ against the solid volume fraction ϕ, where dotted lines for SWCNT and solid lines are for MWCNT, black curves are for water base fluid, blue curves are for ethylene glycol base fluid and red curves are for engine oil base fluid

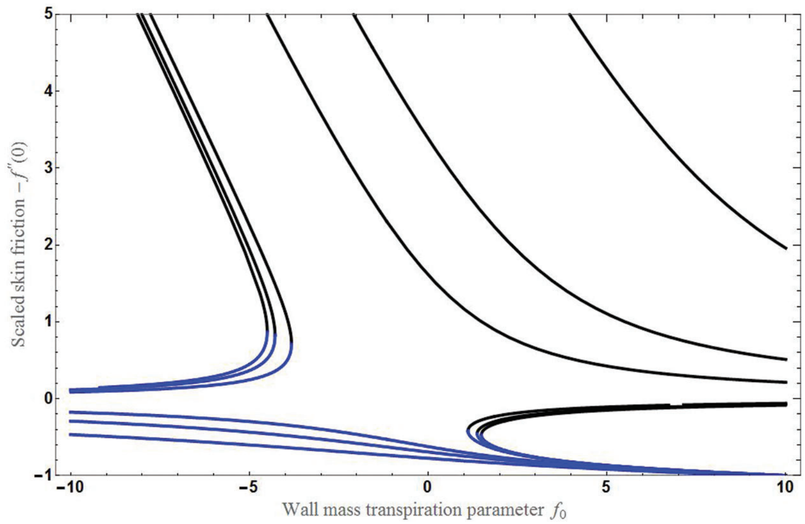

Figure 3: The graph of skin friction verses mass transpiration for various values of permeability parameter ($K_P = 0$, 0.1, 0.3, 3, 5, 10) for 2nd and 3rd roots of Eq. (11) with $\chi_1 = 1$, $\chi_2 = 0.01$ in case of shrinking sheet $(d = -1)$

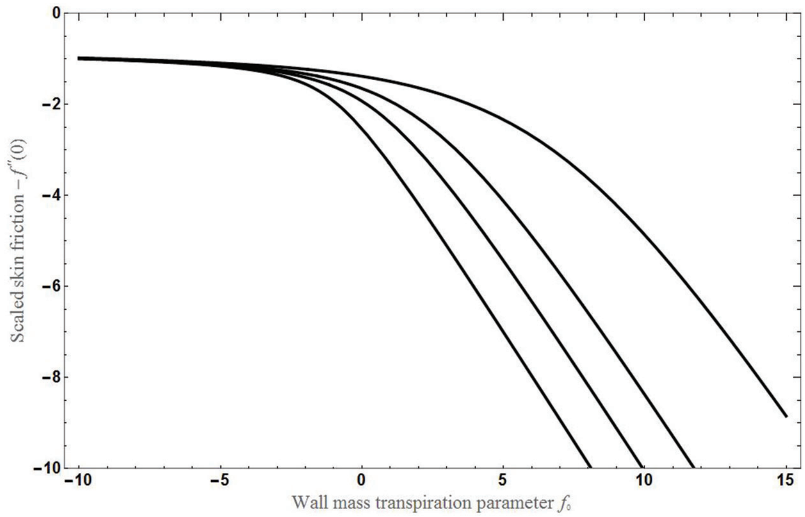

Figure 4: The graph of skin friction verses mass transpiration for various values of permeability parameter ($K_P = 1, 3, 5, 10$) for 1st root of Eq. (11) with $\chi_1 = 1$, $\chi_2 = 0.01$ in case of shrinking sheet ($d = -1$)

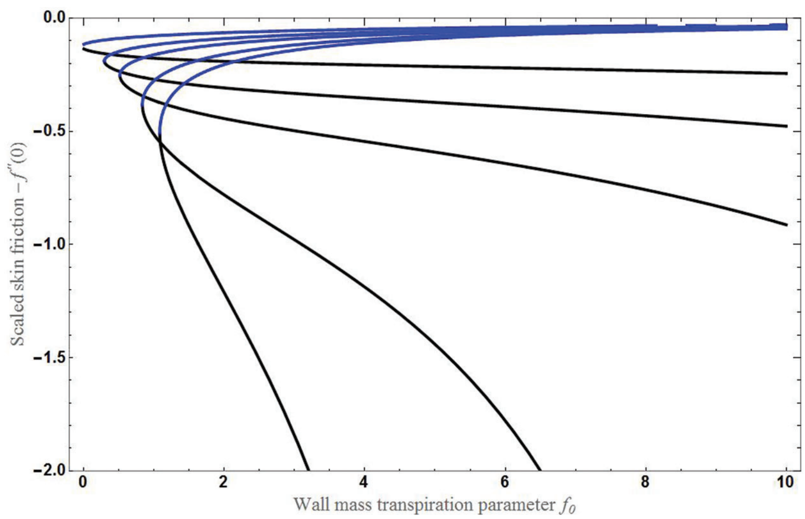

Figure 5: The graph of skin friction verses mass transpiration for various values of ($\chi_1 = 0.5, 1, 2, 3, 5$) for 2nd and 3rd roots of Eq. (11) with $K_P = 0.5$, $\chi_2 = 0.1$ in case of shrinking sheet ($d = -1$)

Variation of Pr with ϕ for MWCNT and SWCNTs is given by,

$$Pr = \frac{(1-\phi)^{5/2}\left[1-\phi+\phi\left(\frac{\rho_{CNT}}{\rho_f}\right)\right]}{(1-\phi)+\phi\frac{(\rho C_p)_{CNT}}{(\rho C_P)_f}}\left[\frac{k_{CNT}+2k_f+2\phi(k_{CNT}-k_f)}{k_{CNT}+2k_f-\phi(k_{CNT}-k_f)}\right]Pr^*, \tag{15}$$

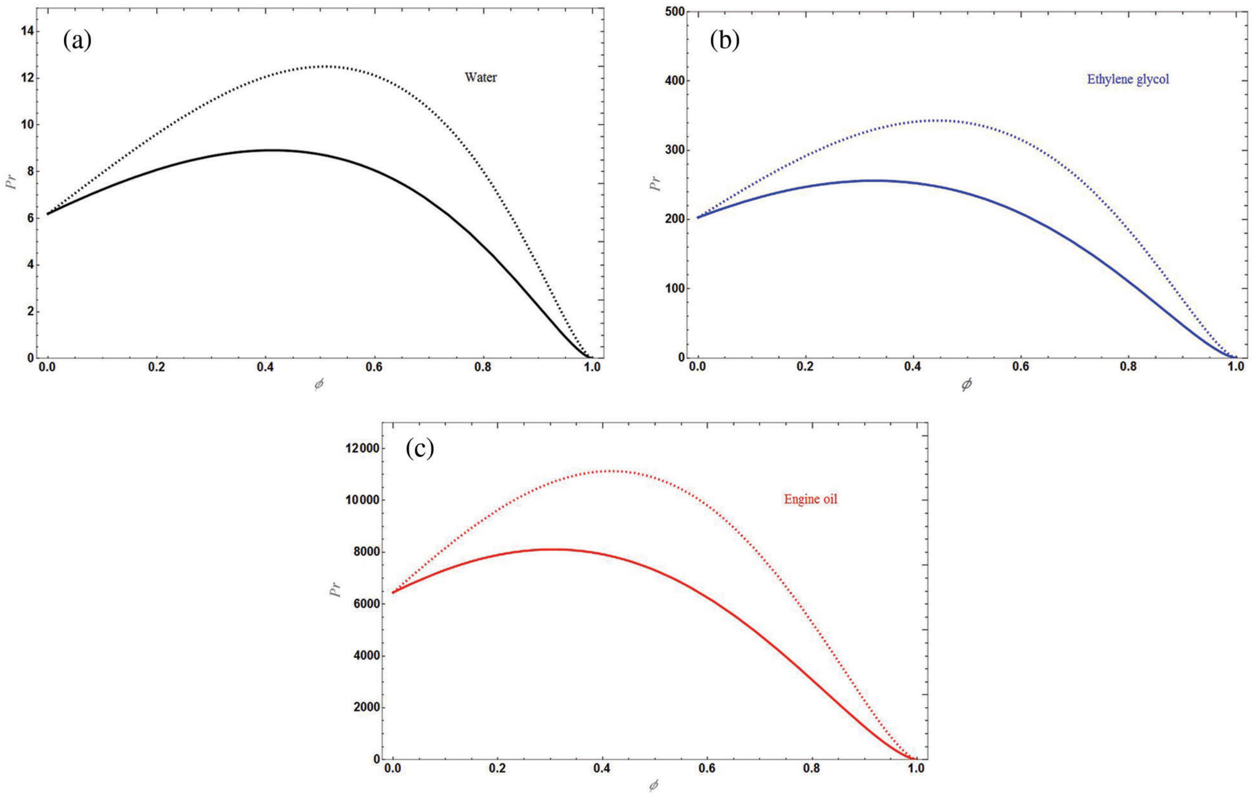

Figure 6: The plot showing the values *Pr* against the solid volume fraction ϕ, where dotted lines for SWCNT and solid lines are for MWCNT

4 Concluding Remarks

The influence of mass transpiration and Navier's slip on the flow of incompressible viscous MWCNT/SWCNT for different base fluids is studied. The concerned effects are analyzed by the help of different graphs for MWCNT/SWCNT. The effects observed are,

- Analytical solution is obtained for velocity and temperature field.
- Prandtl number is lower for water and highest for engine oil.
- Prandtl number for SWCNT is more than that of MWCNT.
- $\sqrt{\beta}$ decreases as the solid volume fraction increases.
- $\sqrt{\beta}$ more for SWCNT than for MWCNT.

Acknowledgement: The author T. Anusha is thankful to Council of Scientific and Industrial Research (CSIR), New Delhi, India, for financial support in the form of Junior Research Fellowship: File No. 09/1207(0003)/2020-EMR-I.

Funding Statement: The authors received no specific funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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