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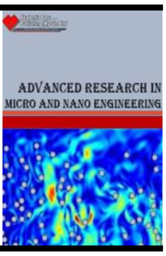

Slip Flow Via Nonlinearly Stretching/Shrinking Sheet in A Carbon Nanotubes

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ABSTRACT

This study is to analyze the problem of slip flow via nonlinearly stretching/shrinking sheet in carbon nanotubes (CNTs) with suction/injection. The governing partial differential equations are transformed into nonlinear ordinary differential equations via the transformation of similarity. The bvp4c solver in Matlab is then used to resolve them numerically. Water is used as the base fluid together with single-wall and multi-wall CNTs. Both velocity slip and thermal slip are considered in this study. The flow parameters effect is investigated, shown in the form of a graph, and physically evaluated for the dimensionless velocity, temperature, skin friction, and Nusselt numbers. The results show that there are unique solutions for stretching sheets and non-unique solutions for shrinking sheets. In addition, increasing the velocity slip parameter σ, suction/injection parameter S and nonlinear parameter β widens the range of solutions, meanwhile increasing the thermal slip σ_t causing the rate of heat transfer to decrease.

1. Introduction

Given its diverse applications, such as in glass fibre production and polymer sheet extraction, the study of flow induced by stretching sheets holds significant importance in fluid mechanics. The investigation initiated by Crane [1] focused on steady boundary layer flow over a linearly stretching surface. Following Crane's work, several researchers delved into expanding and exploring this topic [2-6]. It is worth mentioning that stretching is not strictly linear; hence, various authors have also addressed the matter of non-linear stretching sheets. Vajravelu [7] specifically examined the flow and heat transfer in a viscous fluid over a nonlinearly stretching sheet. They numerically solved the nonlinear ordinary differential equations using a 4th-order Runge-Kutta method. Their conclusion emphasized that heat flows consistently from the stretching sheet to the fluid.

Steady 2D stagnation-point flow of nanofluids past a nonlinearly stretching/shrinking sheet with blowing/suction was studied by Malvandi *et al.,* [8]. They used different nanoparticles such as copper, alumina and titania and the ODEs were solved numerically by the Runge-Kutta-Fehlberg procedure.

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They stated that in both blowing and impermeable cases two solutions exist for shrinking sheets, whereas in the case of suction, an additional solution appears (there are three solutions). While, Hayat *et al.,* [9] studied on boundary layer flow of viscous fluid due to nonlinear curved stretchable surface where they also explored through heat generation or absorption and chemical reaction. Hayat *et al.,* [10] examined the MHD flow of viscous nanofluid caused by nonlinear stretching velocity curved surface and solved the problem by using the HAM method. For pressure distributions, the magnitude of the power-law index parameter is found to increase and the magnitude of the curvature radius decreases for pressure field. Subsequent to their work, numerous researchers [11-13] have investigated diverse boundary layer flow problems considering nonlinear stretching/shrinking sheet.

Choi [14] was the first person who introduce nanofluid which contains a nanometre-sized particle called nanoparticles. Although the behaviour of nanofluids is having a significant impact on improving heat transfer in applications like transportation and biomedicine, carbon still demonstrates positive results due to its potent electrical, mechanical, and thermal properties. Therefore, Choi *et al.,* [15] researched the heat conductivity of oil based CNTs. CNTs are a form of carbon allotrope that comes in single-wall (SWCNTs) and multi-wall (MWCNTs) varieties. Their diameter is measured in nanometres. Since then, numerous studies have uncovered the advantages of CNTs and investigated various boundary layer problems on CNTs [16-18]. CNT stagnation point flow and heat transfer characteristics of a nanofluid were studied by Othman *et al.,* [19] over a shrinking surface with heat sink effects. According to their findings, SWCNT/kerosene is a better nanofluid for flow and heat transmission than MWCNT/kerosene, CNT/water, and ordinary fluid (water).

While some researchers looked at the flow field with a no slip boundary condition, it was equally important to look at how slip boundary conditions affected the flow field. The fluid flow and heat transfer of CNTs over a flat plate with conditions of Navier slip and uniform heat flux were initially considered by Khan *et al.,* [20]. The flow and heat transfer characteristics of CNTs on a moving plate with a slip effect are studied by Anuar *et al.,* [21] and they reveal that the slip parameter was found to widen the range of the possible solutions. Norzawary *et al.,* [22] considered the problem of slip flow via exponentially stretching/shrinking sheet in carbon nanotubes (CNTs) with heat generation effects. They conclude that with an increment in the slip parameter, the solutions range broadens.

Nandy [23] researched the stagnation point boundary layer flow and heat transfer of a non-Newtonian Casson fluid through a stretching surface alongside velocity and thermal slips. The results showed that the increase in the velocity slip parameter caused the velocity of the flow to decrease, while the increase of the thermal slip parameter caused the temperature of the fluid to increase. Ramya *et al.,* [24] analysed the boundary layer viscous flow of nanofluids and heat transfer over a nonlinearly stretching sheet with velocity and thermal slip being considered. They deduced that the velocity profile decreases as the velocity slip parameter increases. In addition, increasing the thermal slip parameter induces decreases in the transfer rates of heat and mass. Nandeppanavar *et al.,* [25] investigated MHD stagnation point flow over a nonlinearly moving plate with momentum and thermal slip effects also non-uniform heat source or sink. Results showed that the velocity slip parameter reduces the flow, velocity and skin friction of the boundary layer but increases the thermal boundary layer, while the temperatures slip parameter decreases the thermal boundary layer. Various boundary layer flow problems considering both velocity and thermal slips have also been investigated by many authors [26-28].

The stagnation point flow problem in carbon nanotubes (CNTs) with suction/injection impacts over a stretching/shrinking sheet was studied [29]. Naramgari and Sulochana [30] also explored the impacts of thermal radiation and chemical reaction on 2D steady MHD flow of a nanofluid via permeable stretching/shrinking sheet with suction or injection. Bakar *et al.,* [31] investigated the steady boundary layer flow over a stretching/shrinking cylinder plus suction effect. All concluded that suction/injection causes the dual solutions to exist and helps to enlarge the heat transfer rate. While, Norzawary *et al.,* [32] stagnation point flow in carbon nanotubes with suction/injection impacts by a nonlinear stretching/shrinking sheet. The range of solutions widen with an increase of S as well as β parameters, whereas, for injection, it decreases the range of solutions.

The goal of this paper is to continue the research conducted by Norzawary *et al.,* [33] where we extend the problem to slip flow via a nonlinearly stretching/shrinking sheet, which considers both velocity and thermal slip parameters. In short, the velocity slip parameter measures slip effects at the fluid-solid interface concerning velocity. In skin friction, it signifies shear stress and drag force, while in the Nusselt number, it is linked to convective heat transfer. A greater slip parameter typically indicates more pronounced slip effects, affecting both frictional forces and heat transfer rates. When there is a temperature difference between the fluid and the solid surface, thermal slip occurs. The thermal slip parameter is a key parameter in the analysis of heat transfer characteristics in slip flow situations.

2. Methodology

Consider an incompressible steady flow concerning stretching/shrinking sheet in CNTs alongside slip and suction/injection effects. The velocity of the free stream and velocity of the sheet are presumed to differ nonlinearly from a steady point of stagnation, which complements to $U_w(x) = ax^n$ and $U_\infty(x) = bx^n$, respectively, where a and b are constants. Both SWCNTs and MWCNTs are used with water base fluid. The boundary layer equations can be addressed as follows [34]

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U_\infty\frac{dU_\infty}{dx}+\frac{\mu_{hnf}}{\rho_{hnf}}\frac{\partial^2 u}{\partial y^2}, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k_{hnf}}{\left(\rho C_p\right)_{hnf}}\frac{\partial^2 T}{\partial y^2}. \tag{3}$$

with conditions of

$$u=U_w+L\frac{\partial u}{\partial y}\ ,\ v=V(x),\ \ T=T_w+M\frac{\partial T}{\partial y}\ \text{ at }\ y=0$$
$$u\to U_\infty,\ \ T\to T_\infty\ \text{ as }\ y\to\infty \tag{4}$$

where L and M denotes the slip factor where its defined as $L=L_1x^{-\frac{n-1}{2}}$ and $M=M_1x^{-\frac{n-1}{2}}$, respectively. L_1 and M_1 is the slip factor's initial length, and mass transfer velocity is $V(x)$. The velocity components in x and y directions are respectively u and v, and nanofluid's temperature is T. μ_{nf} and ρ_{nf} are the thermal diffusivity, viscosity and density of the nanofluid, accordingly, that are provided by Oztop and Abu-Nada [35]

$$\mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}},\ \rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_{CNT},\ \left(\rho C_p\right)_{nf}=(1-\varphi)\left(\rho C_p\right)_f+\varphi\left(\rho C_p\right)_{CNT}$$

$$,\ \frac{k_{nf}}{k_f}=\frac{1-\varphi+2\varphi\dfrac{k_{CNT}}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}}{1-\varphi+2\varphi\dfrac{k_f}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}} \tag{5}$$

where CNTs volume fraction is φ, $(\rho C_p)_{nf}$ and k_{nf} are the heat capacity and conductivity of nanofluid, $(\rho C_p)_{CNT}$, k_{CNT} and ρ_{CNT} are the heat capacity, thermal conductivity and density of CNTs, sequentially, and k_f for fluid density. The term k_{nf}/k_f were adapted from Xue [36] in which the model of Maxwell theory considers the impacts of space distribution of CNTs on heat conductivity.

Adopting the following transformation to signify the governing Eq. (1)-(3) and conditions (4) in a simpler form

$$\psi=\left(\frac{2b\upsilon_f}{n+1}\right)^{\frac{1}{2}}x^{\frac{n+1}{2}}f(\eta),\ \eta=\left(\frac{(n+1)b}{2\upsilon_f}\right)^{\frac{1}{2}}yx^{\frac{n-1}{2}},\ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty} \tag{6}$$

where the variable of similarity is η and the function of a stream is ψ represented as $u=\dfrac{\partial\psi}{\partial y}$ and $v=-\dfrac{\partial\psi}{\partial x}$ that complying with Eq. (1) equivalently. Eq. (2) and (3) and conditions (4) can be simplified to the following ODEs by using Eq. (6)

$$\left[\frac{1}{(1-\varphi)^{2.5}\left(1-\varphi+\varphi\rho_{CNT}/\rho_f\right)}\right]f'''+ff''+\beta\left(1-f'^2\right)=0 \tag{7}$$

$$\frac{1}{\Pr}\left[\frac{k_{hnf}/k_f}{1-\varphi+\varphi(\rho C_p)_{CNT}/(\rho C_p)_f}\right]\theta''+f\theta'=0 \tag{8}$$

$$f(0)=S,\quad f'(0)=\varepsilon+\sigma f''(0),\ \theta(0)=1+\sigma_t\theta'(0),$$

$$f'(\eta)\to 1,\quad \theta(\eta)\to 0$$
(9)

which $\beta=\dfrac{2n}{n+1}$ is the nonlinear parameter which varies from 1 to 2 as n grows from unity to infinity, as stated in Malvandi *et al.,* [8], σ is the velocity slip parameter, σ_t is the thermal slip parameter, $S>0$ is the suction while $S<0$ is injection parameter and ε is the parameter of velocity ratio where $\varepsilon>0$ for stretching and $\varepsilon<0$ for shrinking. The coefficient of skin friction C_f and the number of local Nusselt Nu_x are the physical quantities of concern in this study.

$$C_f = \frac{\mu_{nf}}{\rho_f U_\infty^2}\left(\frac{\partial u}{\partial y}\right)_{y=0} \quad Nu_x = \frac{-xk_{hnf}}{k_f\left(T_f - T_\infty\right)}\left(\frac{\partial T}{\partial y}\right)_{y=0} \tag{10}$$

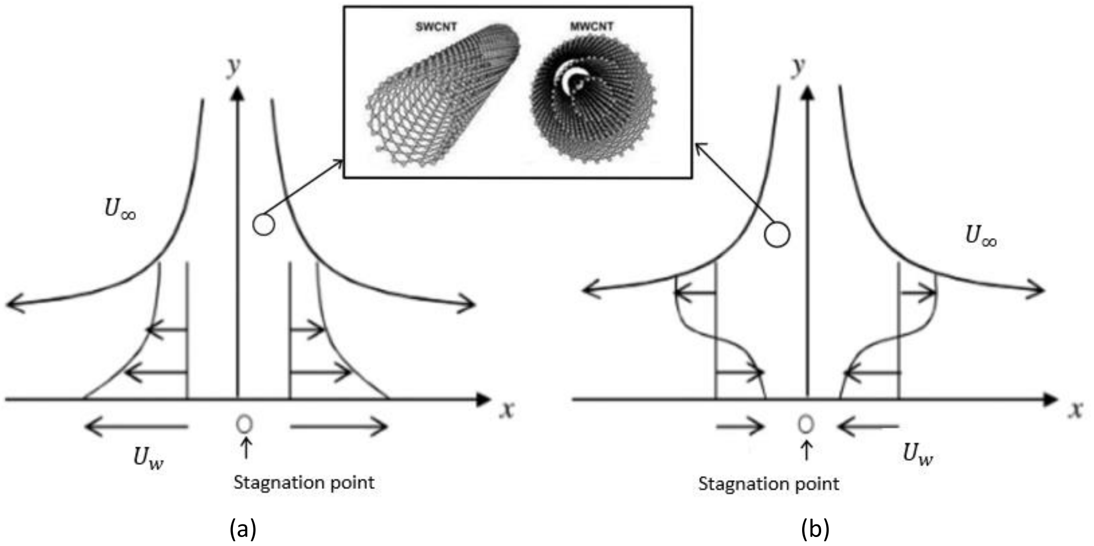
Following the transformations, the quantities of physical interest that we acquire are

$$C_f\left(\mathrm{Re}_x\right)^{1/2} = \frac{1}{\left(1-\varphi\right)^{2.5}} f''(0), \quad Nu_x(\mathrm{Re}_x)^{-1/2} = \frac{-k_{hnf}}{k_f}\theta'(0) \tag{11}$$

where $\mathrm{Re}_x = \frac{U_\infty x}{\nu_f}$ is the number of Reynolds.

3. Results

The system of (7)-(8) and the conditions in (9) are numerically solved using Matlab's bvp4c solver. Both SWCNTs and MWCNTs are taken into account while employing water as the base fluid. The thermophysical properties of the base fluid and CNTs are listed in Table 1. Figure 1 shows the physical model for stretching sheet and shrinking sheet.



(a) (b)

Fig. 1. Physical model for (a) stretching sheet and (b) shrinking sheet

Table 1
Thermophysical properties of CNTs [17]

Physical properties	Base fluids Water (Pr = 6.2)	Nanoparticle SWCNT	 MWCNT
ρ (kg/m^3)	997	2600	1600
c_p (J/kgK)	4179	425	796
k (W/mK	0.613	6600	3000

Figure 2 and 3 illustrate the $f''(0)$ and $-\theta'(0)$ graph with some values of ε, for various values of velocity slip parameter σ for water-SWCNTs. It is noted that the occurrence of slip in the boundary layer results in increased resistance between the fluid and the surface. This, in turn, expands the range within which a solution exists, consequently delaying boundary layer separation. It implies that with the increase in σ, the reduced skin friction and heat loss from the surface increases. This increment occurs in the range where dual solutions exist.

While, Figure 4 shows the $-\theta'(0)$ graph with some values of ε, for various values of the thermal slip parameter σ_t for water-SWCNTs. As σ_t increases, $-\theta'(0)$ decreases. With an increase in thermal slip, the transfer of heat from the sheet to the fluid decreases. As a result, the temperature decreases, signifying a reduction in the heat transfer rate at the surface.

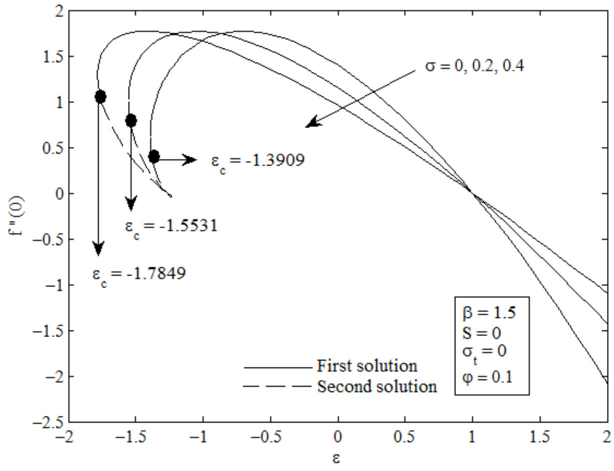


Fig. 2. $f''(0)$ with ε and σ for water-SWCNTs

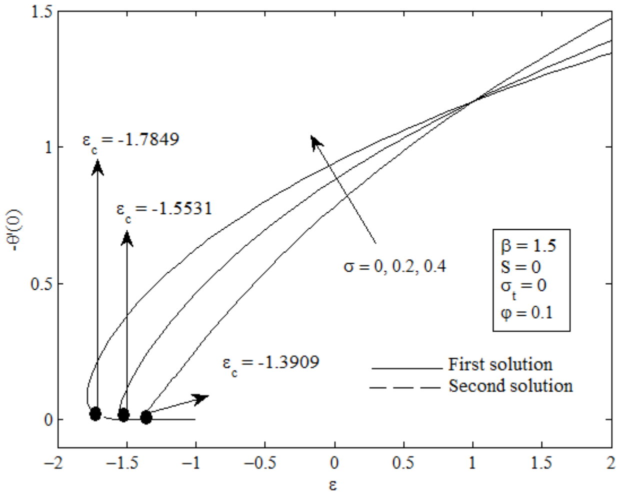


Fig. 3. $-\theta'(0)$ with ε and σ for water-SWCNTs

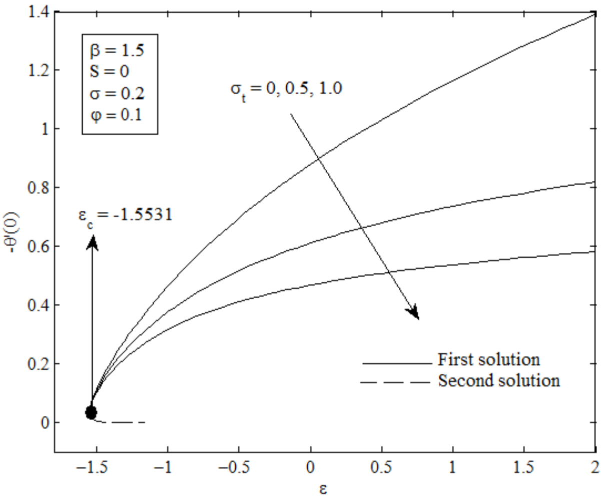


Fig. 4. $-\theta'(0)$ with ε and σ_t for water-SWCNTs

Figure 5 and 6 show the $f''(0)$ and $-\theta'(0)$ with some values of ε, for certain values of stretching/shrinking parameter φ, where $\varphi = 0, 0.1$ and 0.2. It can be seen that dual solutions exist when $\varepsilon_c < \varepsilon \leq -1$, while solution is unique when $\varepsilon > -1$ and when $\varepsilon < \varepsilon_c < 0$, no solutions exist ($\varepsilon_c$ is the critical value of ε). From the figures, we can conclude that an increase of φ causes the skin friction to decrease whereas the heat transfer rate at the surface increases. This is because nanofluids become more viscous by adding CNTs and this also enhances their thermal conductivity.

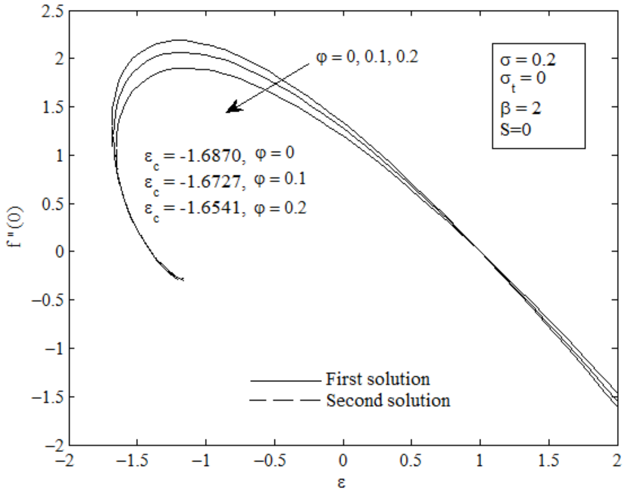


Fig. 5. $f''(0)$ with ε and φ for water-SWCNTs

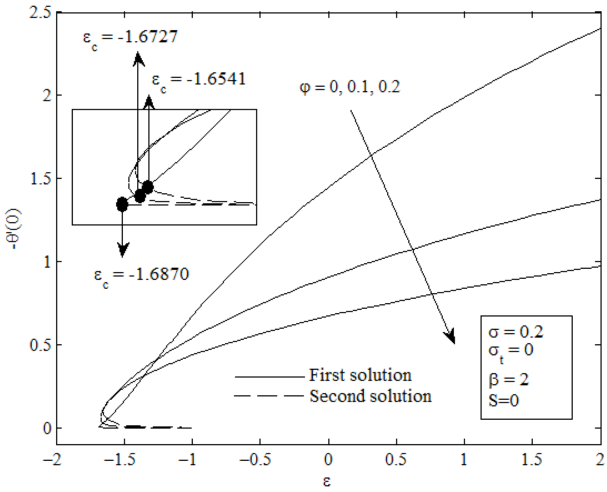


Fig. 6. $-\theta'(0)$ with ε and φ for water-SWCNTs

The graphs of $f''(0)$ and $-\theta'(0)$ for various values of ε are depicted in Figure 7 and 8, corresponding to three distinct nonlinear parameters β values. The conclusion drawn is that β contributes to a broader range of solutions compared to φ and σ. Additionally, an increase in β delays the onset of boundary layer separation. It is noteworthy that an augmentation in β results in an enhancement of both $''(0)$ and $-\theta'(0)$.

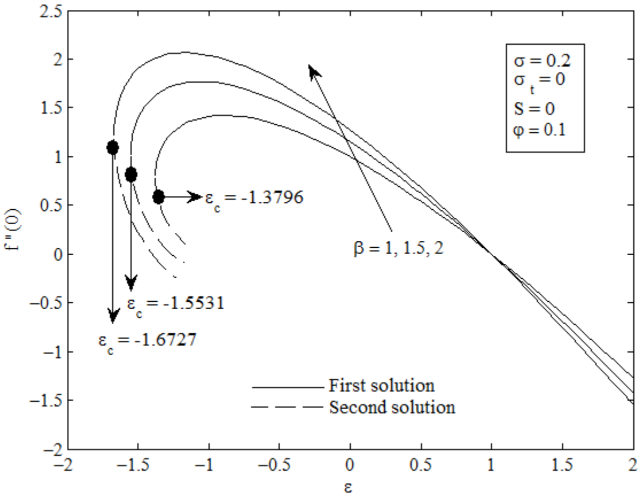


Fig. 7. $f''(0)$ with ε and β for water-SWCNTs

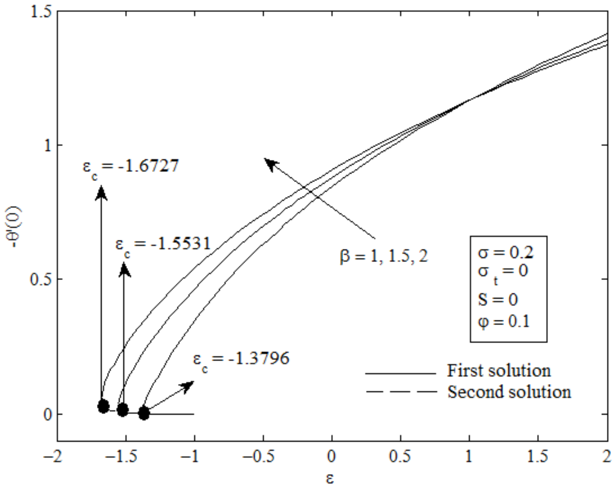


Fig. 8. $-\theta'(0)$ with ε and β for water-SWCNTs

The $f''(0)$ and $-\theta'(0)$ graph for some values of ε, for three various values of suction or injection parameter S are shown in Figure 9 and 10. As S is increased, there is an improvement in the range of solutions. Skin friction and heat loss from the surface are also increasing, so suction ($S > 0$) slows the separation of the boundary layer while it is accelerated by injection ($S < 0$).

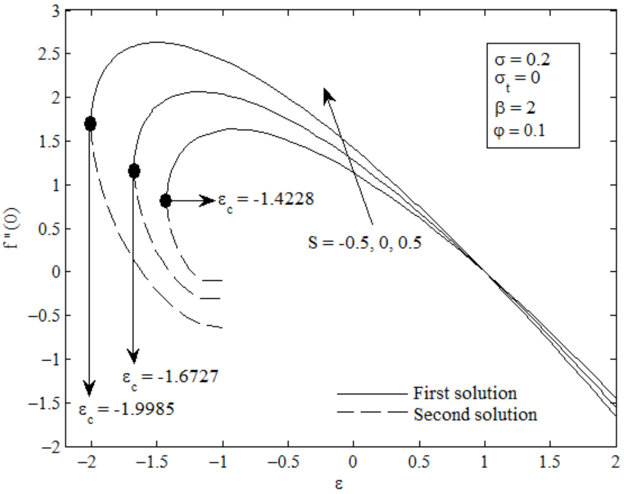


Fig. 9. $f''(0)$ with ε and S for water-SWCNTs

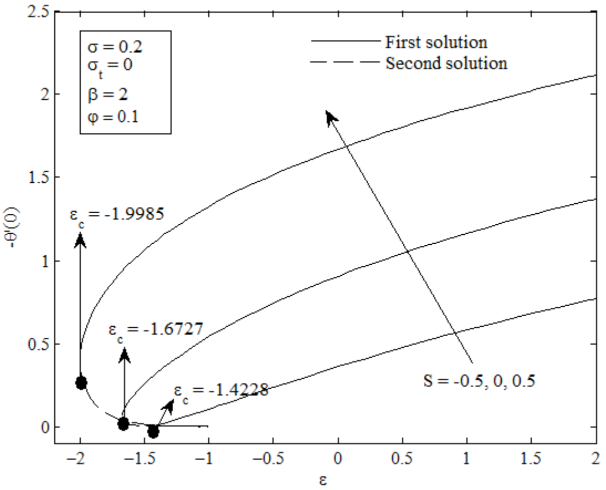


Fig. 10. $-\theta'(0)$ with ε and S for water-SWCNTs

Figure 11 and 12 illustrate the $C_f Re_x^{1/2}$and $Nu_x/Re_x^{1/2}$, given by Eq. (11). It is concluded that as σ increases, $C_f Re_x^{1/2}$ decreases, while $Nu_x/Re_x^{1/2}$ increasing. Convective heat transfer on the surface is enhanced by the presence of slip. Furthermore, SWCNTs are found to be higher than MWCNTs in both $C_f Re_x^{1/2}$and $Nu_x/Re_x^{1/2}$ (refer Table 2). It is because SWCNTs are considered to have a higher density and thermal conductivity than MWCNTs, refer to Table 1. While, $C_f Re_x^{1/2}$and $Nu_x/Re_x^{1/2}$ for two base fluids are shown in Figure 13 and 14, where it shows that kerosene-SWCNT have both higher $C_f Re_x^{1/2}$and $Nu_x/Re_x^{1/2}$. In addition, from Figure 11-14, it shows that these quantities increase almost linearly with φ.

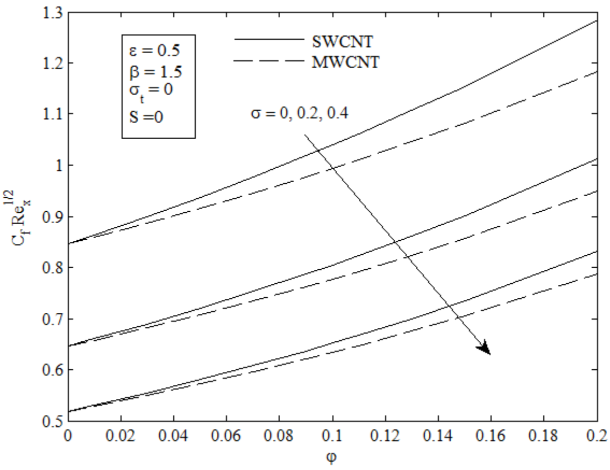


Fig. 11. $C_f Re_x^{1/2}$ with φ and σ

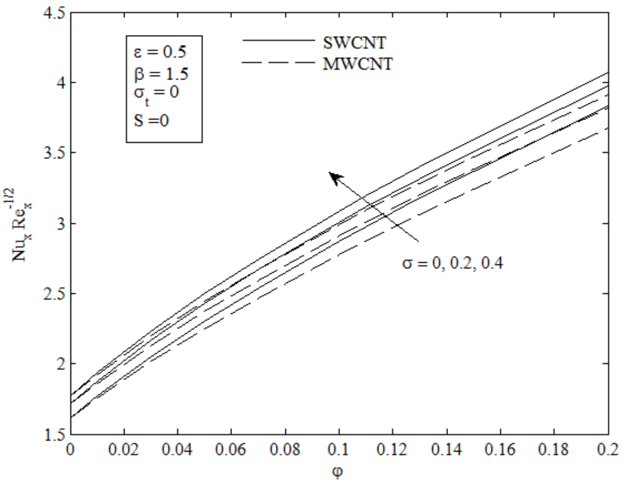


Fig. 12. $Nu_x Re_x^{-1/2}$ with φ and σ

Table 2
$C_f Re_x^{1/2}$ and $Nu_x/Re_x^{1/2}$ for certain values of ε and φ when $\sigma = 2$

ε	φ	$C_f Re_x^{1/2}$		$Nu_x/Re_x^{1/2}$	
		SWCNT	MWCNT	SWCNT	MWCNT
-0.5	0	1.8336	1.8336	0.6674	0.6674
	0.1	2.2535	2.1514	1.5908	1.4680
	0.2	2.7860	2.5658	2.3543	2.1400
0	0	1.4772	1.4770	1.1816	1.1816
	0.1	1.8156	1.7354	2.2765	2.1742
	0.2	2.2445	1.0672	2.9810	2.7354
0.5	0	0.8457	0.8457	1.6156	1.6156
	0.1	1.0394	0.9935	2.8700	2.7760
	0.2	1.2850	1.1834	3.8311	3.6771

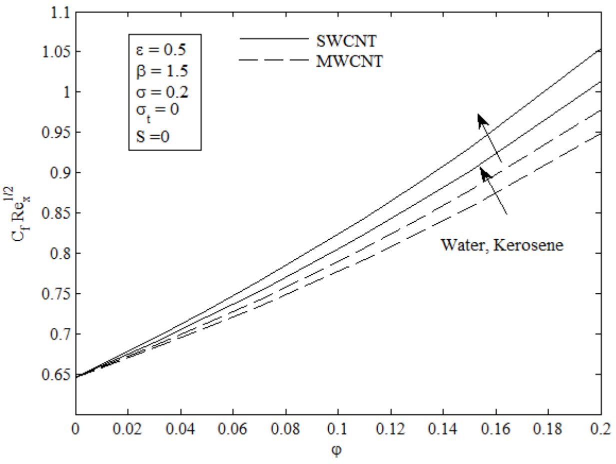


Fig. 13. $C_f Re_x^{1/2}$ with φ and different base fluids

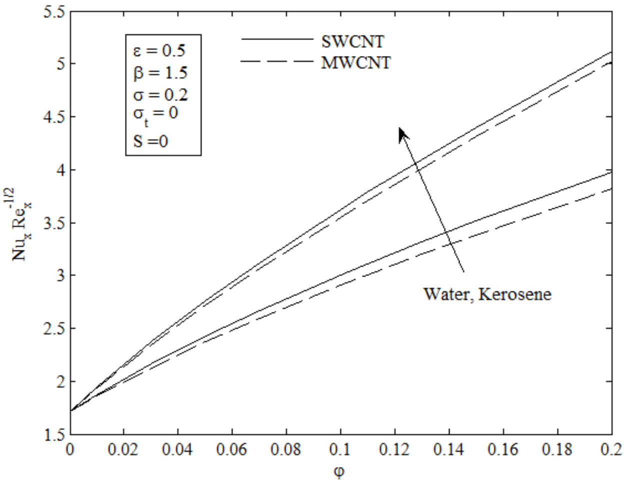


Fig. 14. $Nu_x Re_x^{-1/2}$ with φ and different base fluids

Next, Figure 15 and 16 present the velocity and temperature profiles for different values of σ for water-MWCNTs. It concluded that when σ increases, $f'(\eta)$ increases within the momentum boundary layer thickness for both solutions, while, $\theta(\eta)$ decreases with σ for both solutions and therefore, decreases the thermal boundary layer thickness. Next, Figure 17 presents the temperature profiles for different values of σ_t for water-MWCNTs. Thermal boundary layer thickness decreases with increasing σ_t for both first and second solutions. Since σ_t reduces heat transfer (based on Figure 6), thus temperature is found to decrease.

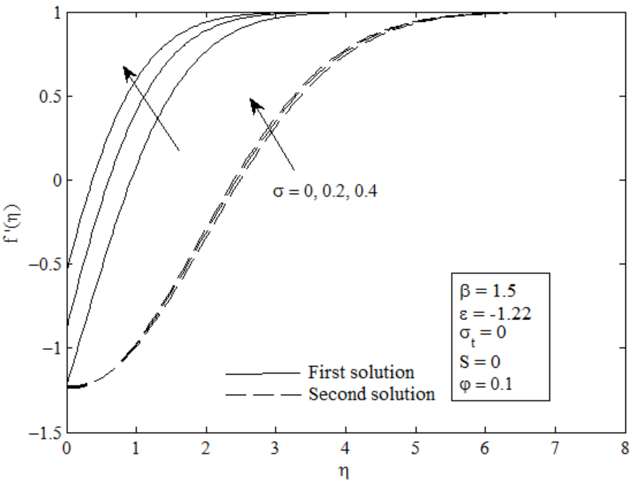


Fig. 15. Velocity profiles for different σ

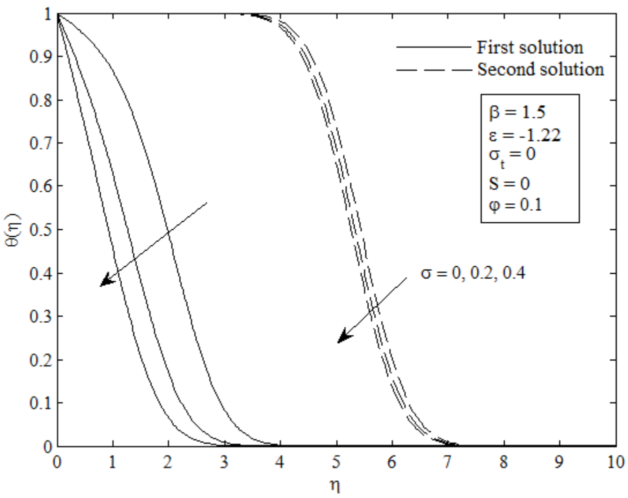


Fig. 16. Temperature profiles for different σ

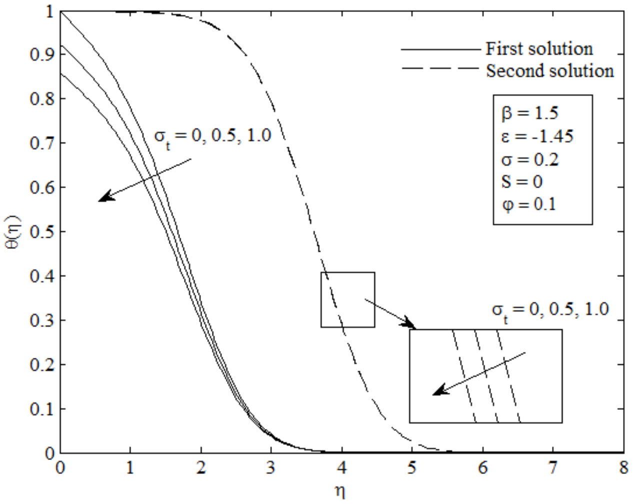


Fig. 17. Temperature profiles for different σ_t

4. Conclusions

A numerical investigation has been conducted on the steady stagnation point flow over a nonlinearly stretching or shrinking surface in a carbon nanotube (CNT) with slip and suction/injection effects. This problem is numerically solved using the bvp4c solver method in Matlab software. The findings of this study suggest that an increase in the velocity slip parameter σ, suction or injection parameter S and nonlinear parameter β leads to a broader range of solutions, implying a delay in the separation of the boundary layer. Conversely, an increase in the carbon nanotubes (CNTs) volume fraction φ has the opposite effect.

Moreover, an increase in the thermal slip parameter σ_t results in a decrease in the rate of heat transfer. Dual solutions exist when $\varepsilon_c < \varepsilon \leq -1$, and it is observed that shrinking sheets exhibit dual solutions, whereas stretching sheets have unique solutions. Lastly, single-walled carbon nanotubes (SWCNTs) prove more effective than multi-walled carbon nanotubes (MWCNTs) in both skin friction and local Nusselt numbers due to their higher thermal conductivity.

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