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Slip Flow Over an Exponentially Stretching/Shrinking Sheet in a Carbon Nanotubes with Heat Generation: Stability Analysis

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ABSTRACT

This study is to analyse the problem of slip flow via exponentially stretching/shrinking sheet in carbon nanotubes (CNTs) with heat generation effects. The governing partial differential equations are transformed into nonlinear ordinary differential equations via 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. The flow parameters effect is investigated, shown in the graphs form, 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, compared to the case of a linearly stretching/shrinking sheet, the region of the stretch/shrink parameter where the similarity solution exists for the case of exponential stretching/shrinking sheet is greater.

1. Introduction

Due to its numerous applications, including in the production of glass fibre and the extraction of polymer sheets, the flow caused by stretching sheets is a significant issue in fluid mechanics. Crane [1] began by looking at the steady boundary layer flow via linearly stretching surface. Numerous researchers became interested in expanding his work after that [2-6]. While most researchers studied for flow over linearly stretching surface, Magyari and Keller [7] were the first to explore flow via exponentially stretching sheet, while the majority of studies focused on flow over linearly stretching surfaces. Following their study, Bhattacharyya and Vajravelu [8] investigated a flow and heat transfer via exponentially shrink surface in a nanofluid. The continuous stagnation point flow and heat transfer in a porous material brought on by an exponentially expanding/contracting sheet were studied by Japili *et al.,* [9]. They came to the conclusion that the stable stagnation point over an exponentially shrinking sheet has a greater range where the similarity solution occurs than a linearly shrinking sheet. There are other researchers who also studied the same cases but with different effects [10-12].

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Choi [13] is the first person who introduced nanofluid where it 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.,* [14] researched the heat conductivity of oil based CNTs. CNTs are a form of carbon allotrope that come in single-wall (SWCNTs) and multi-wall (MWCNTs) varieties. Their diameter is measured in nanometers. Since then, numerous studies have uncovered the advantages of CNTs and investigated various boundary layer problems on CNTs [15-17]. CNT stagnation point flow and heat transfer characteristics of a nanofluid were studied by Othman *et al.,* [18] 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).

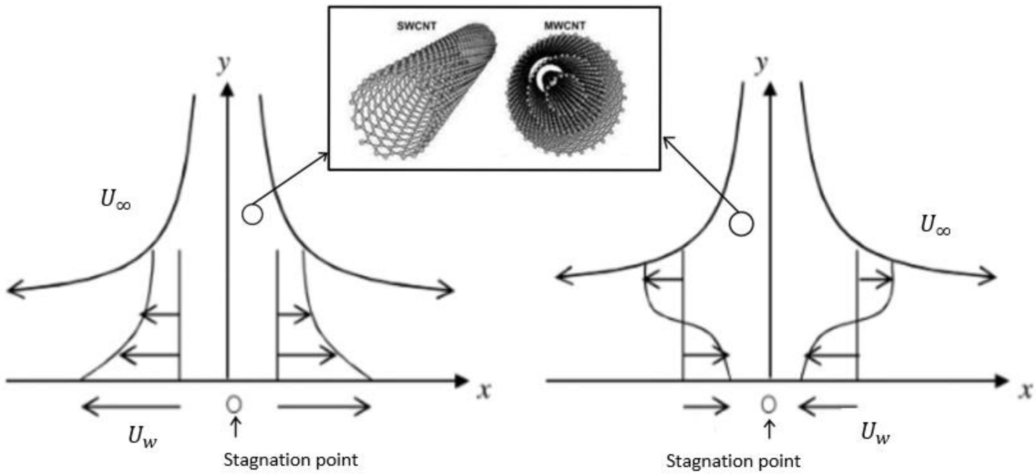
While some researchers looked at the flow field with a no slip boundary condition, it was equally important to look at how slip boundary conditions affected the flow field. The fluid flow and heat transfer of CNTs over a flat plate with conditions of Navier slip and uniform heat flux were initially considered by Khan *et al.,* [19]. The flow and heat transfer characteristics of CNTs on a moving plate with slip effect are studied by Anuar *et al.,* [20] and they reveal that slip parameter was found to widen the range of the possible solutions. After that, many papers also considered slip effects [21-23].

Elbashbeshy and Bazid [24] examined heat transfer via stretching surface alongside internal heat generation or absorption with a power-law velocity distribution. In the presence of chemical reaction and heat source effects, Khan *et al.*, [25] analysed MHD flow of a micropolar fluid across a vertical stretching/shrinking sheet. They discovered that the local Sherwood number has tended to increase with rising values of the chemical reaction parameter while decreasing with rising values of the heat source parameter. Following them, there are numerous paper that considered heat generation [26-28].

In this study, Norzawary *et al.,* [29]'s research is expanded upon. The flow via an exponentially stretch/shrink sheet with addition of heat source effects are considered in this study as opposed to their consideration of flow over a linearly stretch/shrink sheet.

2. Methodology

2D, steady and laminar stagnation point flow of an incompressible nanofluid via exponentially stretch/shrink sheet is considered. The free stream and sheet velocities are assumed to vary exponentially from a fixed stagnation point, which correspond to $U_w(x) = a\, e^{x/L}$ and $U_\infty(x) = b\, e^{x/L}$, accordingly, where a and b are constants, as shown in Figure 1.



(a) (b)

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

The following is a possible formulation for the boundary layer equations [30]

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

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

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}(T - T_\infty) \tag{3}$$

Subject to the boundary conditions

$$\begin{aligned} &u = U_w(x) + L\frac{\partial u}{\partial y}, v = 0, T = T_w = T_\infty + T_0\, e^{\frac{x}{2L}} \quad \text{at } y = 0 \\ &u \to U_\infty(x), T \to T_\infty \ \text{ as } \ y \to \infty \end{aligned} \tag{4}$$

The velocity components in x and y directions are respectively u and v, nanofluid's temperature is T and L_1 denotes the slip factor where is defined as $L = L_1\, e^{-\frac{x}{2L}}$ where L_1 is the initial length of slip factor. α_{nf}, μ_{nf} and ρ_{nf} are the thermal diffusivity, viscosity and density of the nanofluid, accordingly, that are provided by Oztop and Abu-Nada [31]

$$\begin{aligned} &\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}}, \mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}}, \rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_{CNT}, \\ &(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_{CNT}, \quad \frac{k_{nf}}{k_f} = \frac{1-\varphi+2\varphi\frac{k_{CNT}}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}}{1-\varphi+2\varphi\frac{k_f}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}} \end{aligned} \tag{5}$$

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's density. The term k_{nf}/k_f were adapted from Xue [32] 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

$$\eta = y\left(\frac{b}{2\nu_f L}\right)^{\frac{1}{2}} e^{\frac{x}{2L}},\ \ \psi = (2\nu_f L b)^{\frac{1}{2}} e^{\frac{x}{2L}} f(\eta),\ \ \theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty} \tag{6}$$

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

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

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

$$\begin{gathered} f(0) = 0, f'(0) = \varepsilon + \sigma f''(0), \theta(0) = 1 \\ f'(\eta) \to 1, \theta(\eta) \to 0 \text{ as } \eta \to \infty \end{gathered} \tag{9}$$

which $\sigma = L_s\left(\frac{a}{2\nu_f L}\right)^{1/2}$ is the parameter of slip 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.

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

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

$$C_f Re_x^{1/2} = \frac{1}{(1-\varphi)^{2.5}} f''(0),\ \ Nu_x/Re_x^{1/2} = -\frac{k_{nf}}{k_f}\theta'(0) \tag{11}$$

where $Re_x = U_\infty x/\nu_f$ is the local Reynolds number.

The smallest unknown eigenvalue is found via stability analysis. The reason for this is that the results support the same interpretation, according to which the first solution is stable and the second solution is not, and this conclusion was supported by numerous researchers [33–35]. To disturb the replaceable Eq. (2)-(3), the unsteady case is introduced.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_\infty\frac{dU_\infty}{dx} + \frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial y^2}, \tag{12}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho C_p}(T - T_\infty) \tag{13}$$

The new similarity transformation is introduced as follows

$$\eta = y\left(\frac{b}{2\nu_f L}\right)^{\frac{1}{2}} e^{\frac{x}{2L}},\ \ \psi = (2\nu_f L b)^{\frac{1}{2}} e^{\frac{x}{2L}} f(\eta,\tau),\ \ \theta(\eta,\tau) = \frac{T-T_\infty}{T_w-T_\infty}, \tau = \frac{bt}{2L} e^{\frac{x}{L}}, \tag{14}$$

Implementing the new transformation, we obtain

$$\frac{1}{(1-\varphi)^{2.5}(1-\varphi+\varphi\rho_{CNT}/\rho_f)}\frac{\partial^3 f}{\partial\eta^3}+f\frac{\partial^2 f}{\partial\eta^2}-2\left(\frac{\partial f}{\partial\eta}\right)^2+2-2\tau\left[\frac{\partial f}{\partial\eta}\frac{\partial^2 f}{\partial\eta\,\partial\tau}-\frac{\partial f}{\partial\tau}\frac{\partial^2 f}{\partial\eta^2}\right]-\frac{\partial^2 f}{\partial\eta\,\partial\tau}=0 \tag{15}$$

$$\frac{1}{Pr}\frac{k_{nf}/k_f}{\left[1-\varphi+\varphi(\rho C_p)_{CNT}/(\rho C_p)_f\right]}\frac{\partial^2\theta}{\partial\eta^2}+f\frac{\partial\theta}{\partial\eta}-\frac{\partial f}{\partial\eta}\theta-2\tau\left[\frac{\partial f}{\partial\eta}\frac{\partial\theta}{\partial\tau}-\frac{\partial f}{\partial\tau}\frac{\partial\theta}{\partial\eta}\right]-\frac{\partial\theta}{\partial\tau}+Q\theta=0 \tag{16}$$

Subject to the boundary conditions

$$\begin{aligned}&f(0,\tau)=0\,,\frac{\partial f}{\partial\eta}(0,\tau)=\varepsilon+\sigma\frac{\partial^2 f}{\partial\eta^2}(0,\tau),\theta(0,\tau)=1\\&\frac{\partial f}{\partial\eta}(\eta,\tau)\to 1\,,\ \theta(\eta,\tau)\to 0 \text{ as } \eta\to\infty\end{aligned} \tag{17}$$

Next, the following equations are used to detect the stability of the flow [36]

$$f(\eta,\tau)=f_0(\eta)+e^{-\gamma\tau}F(\eta,\tau)\,,\qquad \theta(\eta,\tau)=\theta_0(\eta)+e^{-\gamma\tau}G(\eta,\tau) \tag{18}$$

where γ is parameter of unknown eigenvalue, $F(\eta)$ and $G(\eta)$ are small relative to $f_0(\eta)$ and $\theta_0(\eta)$, respectively. Using Eq (18) into (15)-(16) and letting $\tau\longrightarrow 0$ where $F(\eta)=F_0(\eta)$ and $G(\eta)=G_0(\eta)$ we have the linearized equation as follows

$$\frac{1}{(1-\varphi)^{2.5}(1-\varphi+\varphi\rho_{CNT}/\rho_f)}F_0'''+f_0F_0''+f_0''F_0-(4f_0'-\gamma)F_0'=0 \tag{19}$$

$$\frac{1}{Pr}\frac{k_{nf}/k_f}{\left[1-\varphi+\varphi(\rho C_p)_{CNT}/(\rho C_p)_f\right]}G_0''+f_0G_0'+F_0\theta_0'-f_0'G_0-F_0'\theta_0+\gamma G_0+QG_0=0 \tag{20}$$

with conditions of

$$\begin{aligned}&F_0(0)=0\,,F_0'(0)=\sigma F_0''(0),G_0(0)=1\\&F_0'(\eta)\to 0\,,G_0(\eta)\to 0 \text{ as } \eta\to\infty\end{aligned} \tag{21}$$

One of the boundary criteria needs to be relaxed in light of the research conducted by Harris *et al.,* [37]. Hence, we changed $F_0'(\eta)\to 0$ as $\eta\to\infty$ with the new condition $F_0''(\eta)=1$.

3. Results

The system of (7)-(8) and the conditions in (9) are numerically solved using Matlab's bvp4c solver.Eqs. 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.

Table 1
Thermophysical properties of CNTs (Khan *et al.,* [19])

Physical properties	Base fluids, water (Pr = 6.2)	Nanoparticle	
		SWCNT	MWCNT
$\rho\ (\mathrm{kg/m^3})$	997	2600	1600
$c_p\ (\mathrm{J/kgK})$	4179	425	796
$k\ (\mathrm{W/mK}$	0.613	6600	3000

Figure 2 and 3 show the $f''(0)$ and $-\theta'(0)$ with some values of ε, for certain values of slip parameter σ, where $\sigma = 0, 0.2$ and 0.4. The range of ε values where a solution exists expand as σ grows ($\varepsilon \geq \varepsilon_c$). 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). Additionally, it is found that as σ rises, surface heat loss and reduced skin friction both increases.

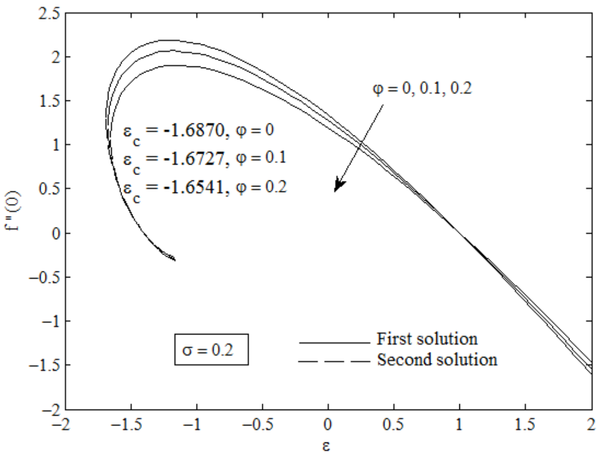


Fig. 2. $f''(0)$ with ε and φ for water-SWCNTs

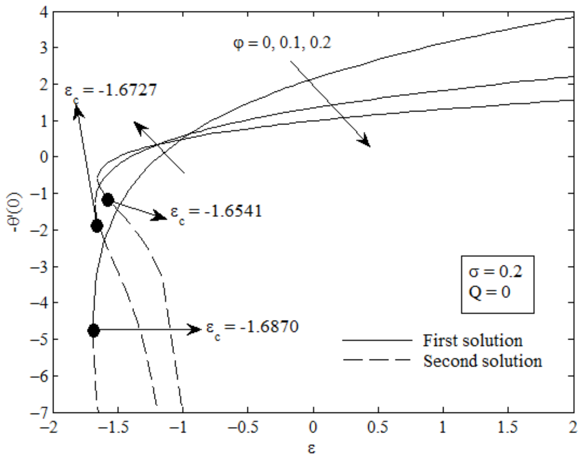


Fig. 3. $-\theta'(0)$ with ε and φ for water-SWCNTs

Figure 4 illustrate $-\theta'(0)$ with some values of ε, for certain values of heat generation parameter Q where $Q = 0, 0.3$ and 0.5. It concluded that when Q increases, the rate of heat transfer decreases.

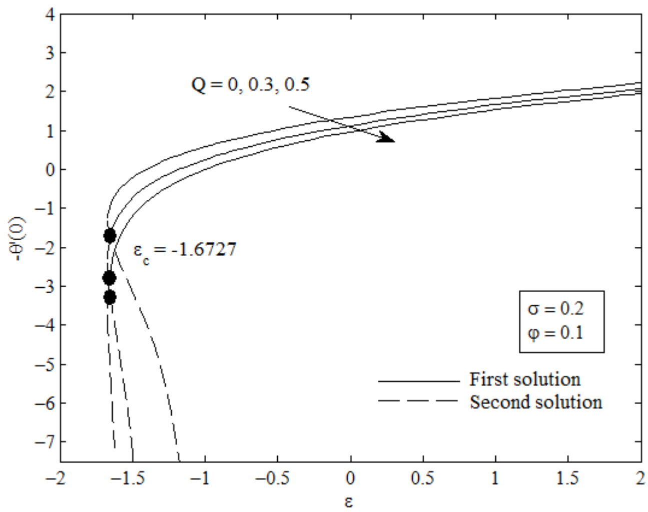


Fig. 4. $-\theta'(0)$ with ε and Qfor water-SWCNTs

Figure 5 and 6 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 $Nu_x/Re_x^{1/2}$. 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 7 and 8, where it shows that kerosene-SWCNT have both higher $C_f Re_x^{1/2}$ and $Nu_x/Re_x^{1/2}$.

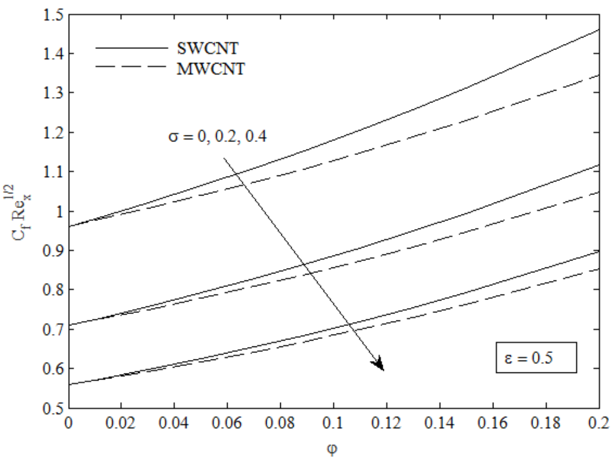


Fig. 5. $f''(0)$ with ε and σ for water-SWCNTs

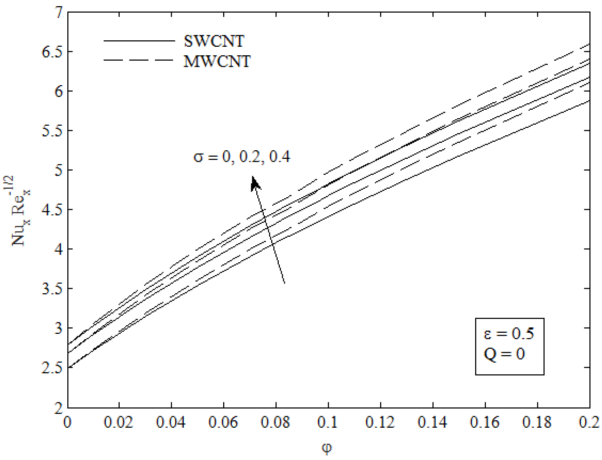


Fig. 6. $-\theta'(0)$ with ε and σ for water-SWCNTs

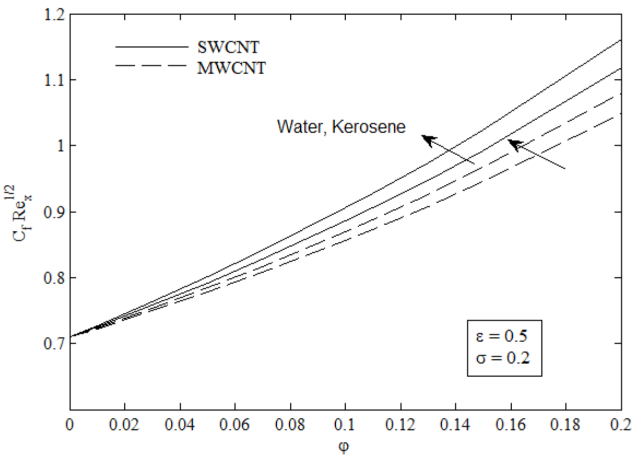


Fig. 7. $f''(0)$ with ε and σ for water-SWCNTs

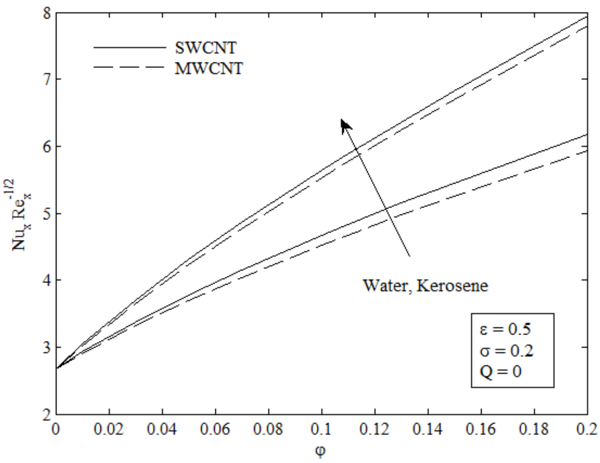


Fig. 8. $-\theta'(0)$ with ε and σ for water-SWCNTs

The velocity and temperature profiles for different base fluids and CNTs are presented in Figure 9-12. From Figure 9-12, all the profiles obtained fulfilled the conditions (9) asymptotically, which then confirmed the presence of the dual solutions shown in Figure 2 and 3. The boundary layer thickness for the first solution is often shown to be lower than for the second solution.

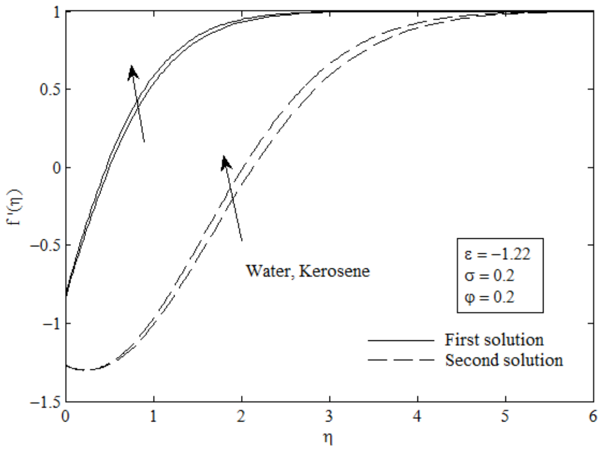


Fig. 9. Velocity profiles for different base fluids

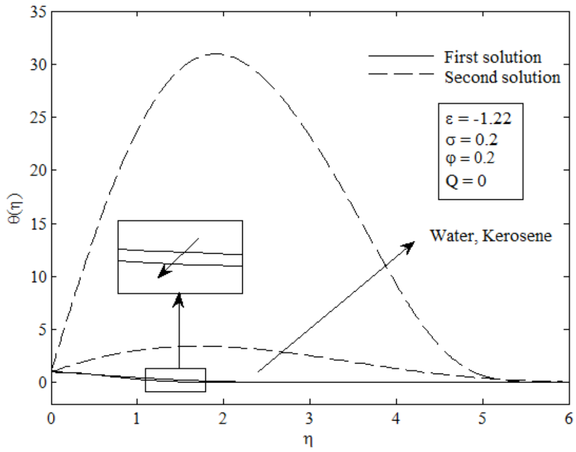


Fig. 10. Temperature profiles for different base fluids

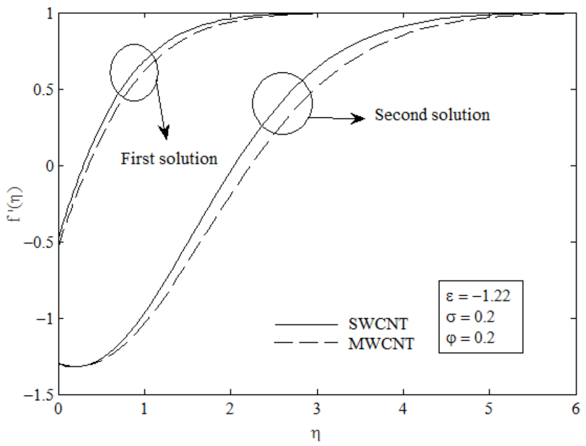


Fig. 11. Velocity profiles for different CNTs

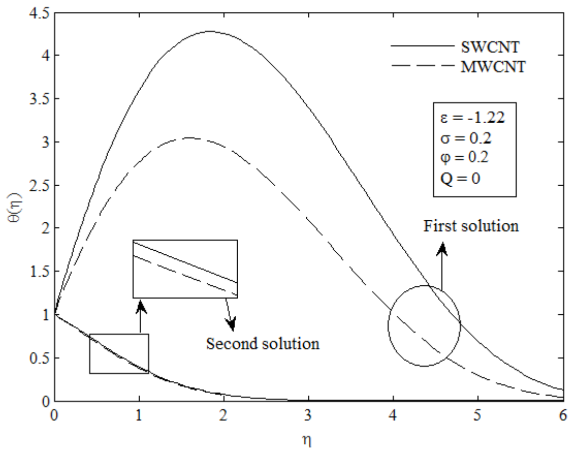


Fig. 12. Temperature profiles for different CNTs

The smallest eigenvalues for various values of are shown in Figure 13. The smallest own values for the upper branch solution are demonstrated to be positive, whereas the opposite is true for the lower branch solution. Figure 13 further demonstrates how, for both similarity solutions as $\varepsilon \longrightarrow \varepsilon_c$,, γ approaches 0, supporting the notion that γ is equal to zero when $\varepsilon = \varepsilon_c$. The first solution was therefore more stable than the second one (refer to Table 2).

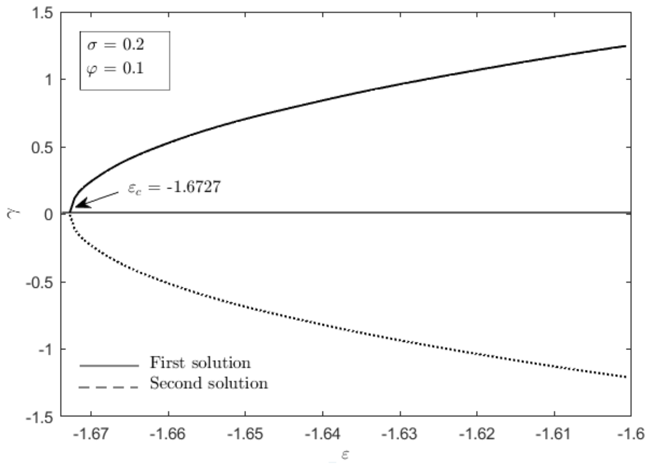


Fig. 13. γ at selected ε for $\sigma = 0.2$ and $\varphi = 0.1$ for water-SWCNTs

Table 2
Smallest eigenvalues γ at selected values of ε for different σ when $\varphi = 0.1$ for water-SWCNTs

σ	ε	Present results	
		First solution	Second solution
$\mathbf{0}$	-1.48701	0.0495	-0.0271
	-1.487	0.0526	-0.0302
	-1.48	0.4326	-0.4064
	-1.4	1.4885	-1.4171
$\mathbf{0.2}$	-1.6727	0.0413	-0.0315
	-1.672	0.1323	-0.1223
	-1.67	0.5276	-0.5125
	-1.6	1.2528	-1.2118
$\mathbf{0.4}$	-1.9515	0.0333	-0.0277
	-1.951	0.1011	-0.0953
	-1.95	0.1675	-0.1615
	-1.9	0.9533	-0.9332

4. Conclusions

This study explored conceptually and assessed the effects of CNT volume fraction, slip, and heat generation on the stagnation point flow past an exponentially stretching/shrinking sheet. The Matlab bvp4c solver was used to solve the issue. The results indicate that

i. Solutions for a stretching sheet are unique while for a shrinking sheet are non-unique.
ii. With an increment in the slip parameter, the solutions range broadens, but with a rise in heat generation, it narrows.
iii. Single walled CNTs outperform multi walled CNTs in terms of skin friction and local Nusselt number.
iv. The first solution is stable while the second solution is not, based upon the stability analysis.

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