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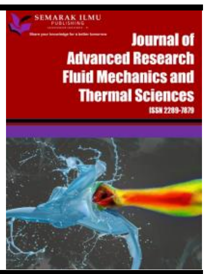

The Significant Effect of Hydromagnetic on Carbon Nanotubes Based Nanofluids Flow and Heat Transfer Past a Porous Stretching/Shrinking Sheet

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ABSTRACT

The 2D steady flow model of carbon nanotubes-based nanofluids and heat transfer past a porous stretchable or shrinkable sheet is studied analytically and numerically. A mathematical model that is governed by a system of partial differential equations (PDEs) subjected to boundary conditions is transformed into a system of dimensionless ordinary equations (ODEs). The non-dimensional ODEs system is solved using MATLAB bvp4c solver. The effect of various parameters such as magnetic field, porosity, the stretching/ shrinking velocity parameter, and CNTs volume friction on velocity and temperature profile, skin friction, Nusselt number and heat transfer rate are investigated numerically and the results are presented using graphical illustration. From the results, non-unique solutions are obtained in the cases where the sheet is shrunk, the magnetic parameter less than 0.1, or the porosity parameter is less than 30. Besides, the increment of magnetic field into the flow will increase both the skin friction and the heat transfer coefficient, while on the contrary, the decreasing in both the skin friction and the heat transfer coefficient will occur if the porosity parameter is raised. We are also showing that SWCNTs is more effective both in the skin friction and the heat transfer coefficient compared to MWCNTs.

1. Introduction

The Investigation of boundary layer flow over a diverse type of geometric shapes and fluids has drawn continued consideration by many researchers. A considerable amount of literature has been published discussing the behaviour of boundary layer flow. From these publications, the study of boundary layer flow past stretching sheets has revealed the importance of computational and physical interests in various applications.

From relevant scientific publications, one of them is Crane [1] who became the first researcher discovered analytically the two-dimensional (2D) steady flow over a linearly stretching plate in 1970.

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Up to now, several studies have demonstrated numerically the flow over different stretchable/shrinkable shapes including shrinking/stretching cylinder by Ali *et al.,* [2] and Dzulkifli *et al.,* [3], disk by Soid *et al.,* [4] and Khashi'ie *et al.,* [5], and wedge by Awaludin *et al.,* [6] and El-Dawy and Gorla [7]. To scrutinise the flow in different fluids past the stretching/shrinking sheet, several authors emerged as one of an active group to study the flow of micropolar fluid, viscous fluid, and Casson fluid, respectively [8-10]. Khan and Pop [11] utilized nanofluids but they only investigated on extending sheet.

The discovery of 2D-stagnation flow in 1911 by Hiemenz [12] triggered a huge amount of innovative scientific inquiry. Theoretically, Merkin *et al.,* [13] stated that all solid surfaces travelling in a fluid exhibit stagnation-point flows, which interpret the fluid motion near the stagnation area at the front of a blunt-nosed body. In an analysis of heat transfer at the stagnation zone, Liu *et al.,* [14] found the highest heat transfer coefficient was detected in this region.

The first discussion and analysis of the boundary layer of nanofluids flow at the stagnation region past a stretching/shrinking sheet was discovered analytically and numerically by Bachok *et al.,* [15]. By working with three types of nanoparticles, namely copper, alumina, and titania, which these particles suspended in water, dual solutions were found when the flow moved shrinkingly to the stagnation point as depicted in Figure 1. Then, the work inspired Bachok *et al.,* [16] to extend their work using a different approach by investigating the flow over an exponentially stretching/shrinking sheet. They observed that the stretching sheet produced only one solution, while multiple solutions obtained by the shrinking sheet. Different particles of nanofluids, for example, Al_2O_3, and Cu by Mahmood *et al.,* [17] have also been tested to examine the behaviour of the flow and enhance the heat transfer. Nanofluids have been a major area of research in fluid mechanics since Choi and Eastman [18] introduced them in 1995, particularly in raising the fluid velocity and enhancing the heat transfer rate. Effective nanofluids can be prepared by selecting nanoparticles from metal, non-metal or carbon-based and diffusing them in a base liquid such as water, kerosene, and ethylene glycol. Japar *et al.,* [19] found that water has become the most favourable base fluid in many works.

Due to the high demand of carbon-based materials, especially carbon nanotubes (CNTs), and the rise CNTs utilisation reviewed by Trivedi and Reecha [20], such as in sensors, genetic engineering, and batteries, recent work by Norzawary *et al.,* [21] carried out an important investigative plan to view the flow in CNTs nanofluids in the presence of suction and injection effects. Based on Trivedi and Reecha [20], CNTs are recommended to be selected for this model as these particles possess powerful thermal properties as well as electrical, and mechanical criteria. In fact, CNTs were proposed by Meskher *et al.,* [22] as an excellent material for designing biosensors in order to detect Covid at a fast rate. From Norzawary *et al.,* [21], they found that the suction and injection effects executed contradictory outcomes on producing the type of solutions for values of the reduced skin friction, $f''(0)$ and the heat transfer coefficient, $-\theta'(0)$. They also noticed that single-walled carbon nanotubes (SWCNTs) performed better than multi-walled carbon nanotubes (MWCNTs) in both skin friction and local Nusselt number. Practically, Mamedov *et al.,* [23] discovered that SWCNTs and MWCNTs can be differentiated according to the number of graphene layers, distortion chance, purity, and the elasticity of graphene layers to be glued together and rolled up.

As Merkin *et al.,* [24] reported that research on nanofluids is still ongoing and a better understanding of the nanofluids flow and heat transfer properties of nanofluids should be proposed precisely, we are encouraged to extend the work from Bachok *et al.,* [15] and Norzawary *et al.,* [21]. Referring to some parameters that were taken into consideration by Negi *et al.,* [25], our newly suggested model deals with both stretching and shrinking sheet. From the literature, the previous investigation by Negi *et al.,* [25] only discussed on extending sheets. Hence, the novelty of this study can be defined by attempting the influence of hydromagnetic and porosity on CNTs nanofluids flow and heat transfer over both linearly stretching and shrinking surfaces, which these effects have not been extensively analysed using both analytical and numerical methods by Norzawary *et al.,* [21]. Besides, although studies on CNTs flow have been performed by many researchers past different surfaces, to date, interestingly, research has yet to numerically examine the effect on the above-proposed parameters for the stagnation-point flow over the stretching or shrinking sheet. Therefore, the main objective of this current study is to analytically and numerically investigate the effect of hydromagnetic and porosity factors on the boundary layer flow of CNTs-based water nanofluids. This study will significantly contribute to numerical computations and engineering applications.

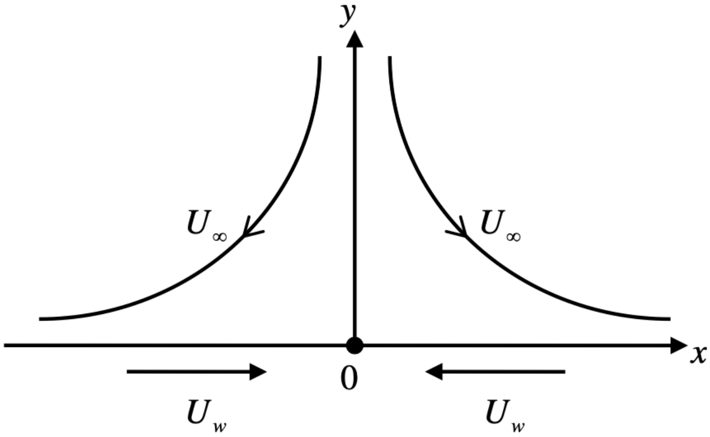

Fig. 1. Schematic diagram [15]

2. Methodology
2.1 Mathematical Formulation

We begin our formulation by letting a steady stagnation-point flow towards a horizontally stretching or shrinking sheet. This flow is moving in the presence of CNTs water-based nanofluids at a constant temperature, T_w, and the Prandtl number, Pr = 6.2. The thermophysical and physical properties of CNTs nanofluids are illustrated in Table 1 and Table 2.

Table 1
Thermophysical properties of CNTs and base fluids based on the previous work by Samat *et al.,* [26]

Properties	Nanoparticles	
	SWCNTs	MWCNTs
ρ (kg/m^3)	2,600	1,600
C_p (J/kg K)	425	796
k (W/m K)	6,600	3,000

Table 2
Physical properties of CNTs and base fluids based on the previous work by Samat *et al.,* [26]

Properties	CNTs Nanofluids
Dynamic viscosity	$\mu_{nf} = \mu_f/(1-\phi)^{2.5}$
Density	$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_{CNT}$
Effective kinematic viscosity	$\nu_{nf} = \mu_f/\rho_{nf}$

Our 2D model for laminar and incompressible flow is governed by previous works performed by Bachok *et al.,* [15], Norzawary *et al.,* [21], and Negi *et al.,* [25]. By modifying the momentum and thermal equations from Anup *et al.,*'s Model [25] and ignoring the effect of slip boundary condition, the equations of continuity, momentum and energy are constructed as follows

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \quad (1)$$

$$u\frac{\partial(u)}{\partial x}+v\frac{\partial(v)}{\partial y}=\frac{\mu_{nf}}{\rho_{nf}}\frac{\partial^2 u}{\partial y^2}+U_\infty\frac{dU_\infty}{dx}+\left(\frac{\sigma}{\rho_{nf}}B_0^2\right)(U_\infty-u)+\left(\frac{\mu_f}{\rho_f k_0}\right)(U_\infty-u), \quad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}. \quad (3)$$

where k_0, B_0, and σ represent the permeability, the strength of magnetic field, and electric conductivity, respectively. The free stream velocity, U_∞, is normal to the sheet. This system is subjected to the following boundary conditions

$$u=U_w, v=0, T=T_w \text{ at } y=0, u\to U_\infty, T\to T_\infty, \text{as } y\to\infty. \quad (4)$$

U_∞ is designed in linear form such that $U_\infty=ax$, where a is a constant value and always considered a positive value. The flow is traveling linearly extending or shrinking sheet with the velocity $U_w=bx$, where the values of b can be classified into two cases. If we take the value of $b<0$, then we deal with the shrinking surface, while the stretchable surface will communicate with $b>0$.

To taper off the complexity of numerical approximation and generalise the model to scalable systems, as mentioned by Kenny and Nicolais [27], we convert our partial differential equations (PDEs) model into a dimensionless ordinary differential equations (ODEs) model. The transformation of this model from the PDEs form to the ODEs form can reduce the number of independent variables from two variables x, and y to single variable, η.

2.1 Analytical Method

Before we change the PDEs form of Eq. (1) to Eq. (3) into non-dimensional ODEs form, we introduce the velocity components, u, and v. These components are written in the following equations

$$u=\frac{\partial\psi}{\partial y}, \quad (5)$$

$$v=-\frac{\partial\psi}{\partial y}, \quad (6)$$

where u, and v are depending on x, y, and ψ is a dimensionless stream function. The non-dimensional similarity variables of boundary layer thickness, η, stream function, ψ, solution for steady flow, f, and solution for temperature, θ, are written as

$$\eta=\left(\frac{a}{\nu_f}\right)^{1/2} y, \quad (7)$$

$$\psi(\eta) = \left(\nu_f\right)^{\frac{1}{2}} x f(\eta), \tag{8}$$

$$\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \tag{9}$$

where ν_f denoted as the kinematic viscosity of fluid. The term of T, T_w, and T_∞ are representing to the temperature of CNTs nanofluids, the surface temperature, and the ambient temperature, respectively.

Employing the similarity variables from Eq. (7) to Eq. (9) for solving PDEs, then we can switch over the PDEs Model to dimensionless ODEs for Eq. (2)-(4) as following expressions

$$\frac{1}{(1-\phi)^{(2.5)} + \left(1 - \phi + \frac{\phi \rho_{CNT}}{\rho_f}\right)} f'''(\eta) + f(\eta) f''(\eta) + (M + Da^{-1})\left(1 - f'(\eta)\right) + 1 = 0, \tag{10}$$

$$\frac{1}{\mathrm{Pr}} \frac{\left(\frac{1-\phi+2\phi\frac{k_{CNT}}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}}{1-\phi+2\phi\frac{k_f}{k_{CNT}-k_f}\ln\frac{k_{CNT}+k_f}{2k_f}}\right)}{\left(1 - \phi + \frac{\phi(\rho Cp)_{CNT}}{(\rho Cp)_f}\right)} \theta''(\eta) + f(\eta)\theta'(\eta) = 0, \tag{11}$$

with subject to boundary conditions

$$f'(\eta) = \varepsilon, f(\eta) = 0, \theta(\eta) = 1, \text{at}\ \eta = 0, f'(\eta) \to 1, \theta(\eta) \to 0, \text{as}\ \eta \to \infty, \tag{12}$$

where ε is the velocity parameter, such that $\varepsilon = b/a$. The term of ε becomes one of the key parameter that affects the behaviour of the boundary layer of CNTs flow and generate one solution, more than one solution, or no solution for $f''(0)$ and $-\theta'(0)$. From Eq. (10), we can set M as the magnetic field parameter or also knows as Hartman number as applied Soid *et al.,* [8], and Da as the porosity parameter or Darcy number as utilised by Negi *et al.,* [25].

To measure the physical quantities that can be applied in studying the application of the model, we define the local skin friction coefficient, C_f, and the local Nusselt number, Nu_x, based on the definition from Bachok *et al.,* [15] in the following equation

$$C_f = \frac{\tau_w}{\rho_f U^2}, \tag{13}$$

and

$$Nu_x = \frac{x}{k_f (T_w - T_\infty)}, \tag{14}$$

where τ_w and q_w is the surface shear stress and the heat flux, respectively. From Negi *et al.,* [25], τ_w and q_w can be written as

$$\tau_w = \mu_{nf} \left(\frac{\partial u}{\partial y}\right)_{y=0}, \tag{15}$$

$$q_w = -k_{nf} \left(\frac{\partial T}{\partial y}\right)_{y=0}. \tag{16}$$

Applying the similarity variables from Eq. (7) to Eq. (9), then we obtain the local skin friction, $C_f\sqrt{Re_x}$, and the local Nusselt number, $Nu_x/\sqrt{Re_x}$as follows

$$C_f\sqrt{Re_x} = \frac{1}{(1-\phi)^{(2.5)}} f''(0), \tag{17}$$

$$Nu_x/\sqrt{Re_x} = -\left(\frac{k_{nf}}{k_f}\right)\theta'(0), \tag{18}$$

where $Re_x = \frac{U_\infty x}{\nu_f}$ is the local Reynold number.

3. Result and Discussion

The computational strategy to interpret the boundary value problem for Eq. (10) to Eq. (12) can be conducted by solving them numerically in MATLAB using the bvp4c package. Our analysis of this model operated successfully by defining the relevant range of various parameters that have been demonstrated effectively by many scientific researchers. The main parameters are the magnetic parameter, M, as referred to by Salleh *et al.,* [28], Asshaari *et al.,* [29] and Mansur *et al.,* [30], the porosity parameter, Da, from Sheikholeslami [31], the stretching or shrinking velocity parameter, ε, from Bachok *et al.,* [15], the nanoparticle volume fraction, ϕ, based on Sulaiman *et al.,* [32], and the dimensionless boundary thickness, η, from Anuar *et al.,* [33].

In this section, various numerical outcomes, comprising the reduced skin friction, $f''(0)$, the heat transfer coefficient, $-\theta'(0)$, the velocity profile, $f'(\eta)$, the temperature profile, $\theta(\eta)$, the local skin friction coefficient, $C_f\sqrt{Re_x}$, and the local Nusselt number coefficient, $Nu_x/\sqrt{Re_x}$ for SWCNTs-water based and MWCNTs-water based are carried out and visualised graphically using the above parameters.

In order to investigate the effects of M on $f''(0)$ and $-\theta(0)$ for SWCNTs-water based flow, the values of M and ε are varied in the intervals of $0 \leq M \leq 0.5$ and $-2 < \varepsilon \leq 2$ respectively, while other parameters remain invariable at Da = 100, Pr = 6.2, and ϕ = 0.1. From Figure 2 and Figure 3, attractively, the range of ε, such that $\varepsilon_c \leq \varepsilon < 0$ is producing paired solutions, while the existing of single solution and no solution are detected at $\varepsilon \geq 0$ and $\varepsilon < \varepsilon_c$, respectively, where ε_c is defined as the intersection value between first and second solutions. Besides, impressively, a rising number of M is observed to slow down the boundary layer separation. Similarly with previous research, the delay of the boundary layer separation in this analysis meets the experimental work organised by Dietiker and Hoffmann [34] in the case of M is increased.

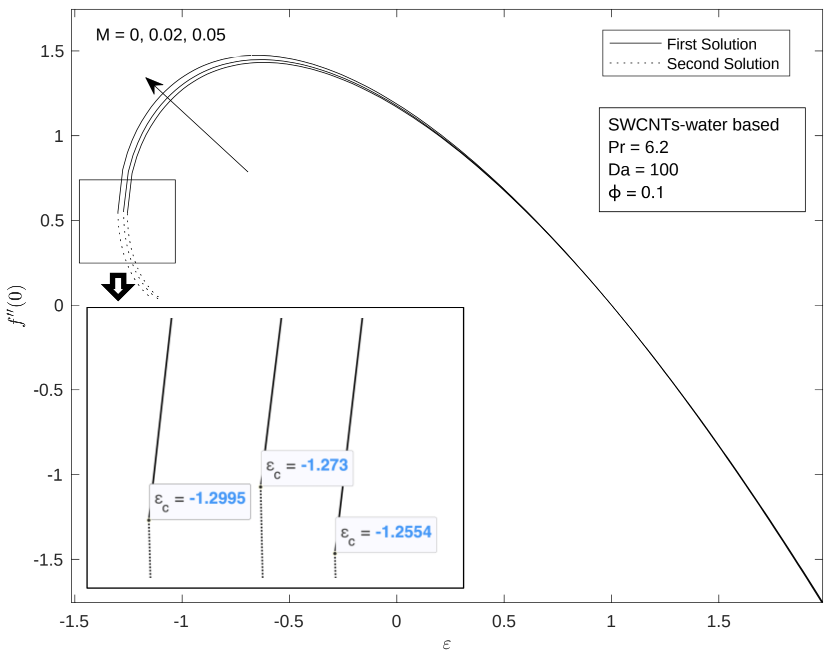

Fig. 2. Variation of $f''(0)$ with different M and ε for SWCNT- water based

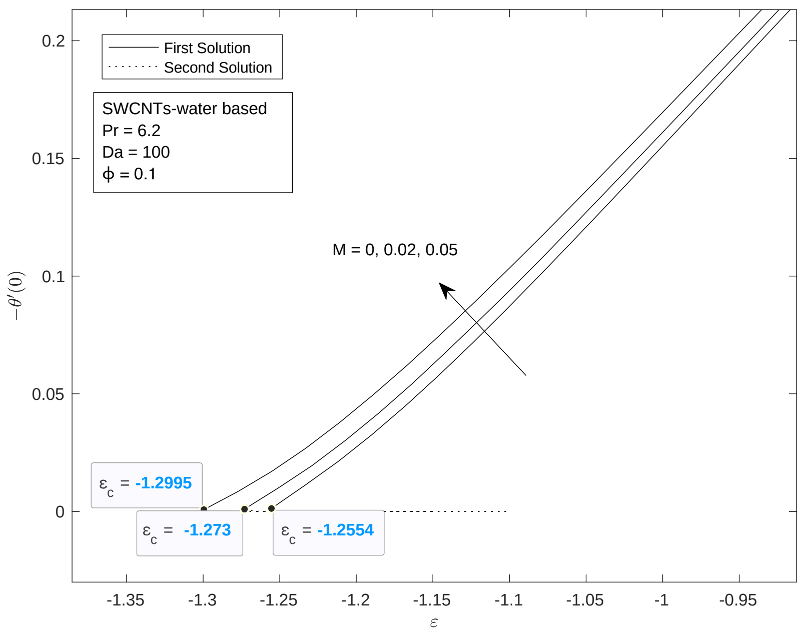

Fig. 3. Variation of $-\theta'(0)$ with different M and ε for SWCNT- water based

By setting the different values of Da from 30 to 100 at constant values of M, Pr, and ϕ, then we can see the influence of Da and ε on $f''(0)$ and $-\theta'(0)$ for MWCNTs-water based flow as exhibited in Figure 4 and Figure 5. The unique and non-unique are lied in the region of $\varepsilon \geq 0$ and $\varepsilon_c \leq \varepsilon <$ 0 0, respectively, while the area of $\varepsilon < \varepsilon_c$, is not initiating any solution for $f''(0)$ and $-\theta'(0)$. However, a contradictory result for the boundary layer separation phenomenon is identified as illustrated in Figure 4 if the value of Da increases. The increment of Da can separate the boundary layer at an accelerated rate.

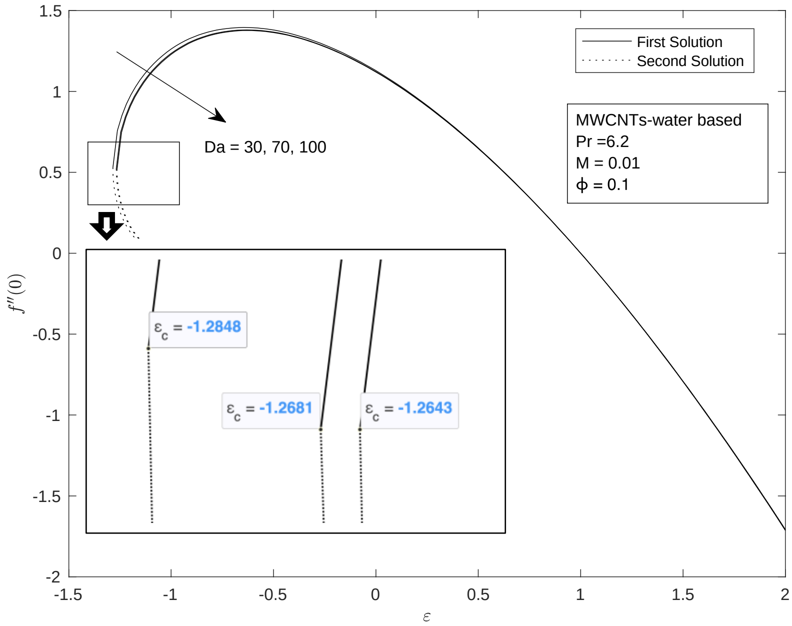

Fig. 4. Variation of $f''(0)$ with different Da and ε for MWCNT-water based

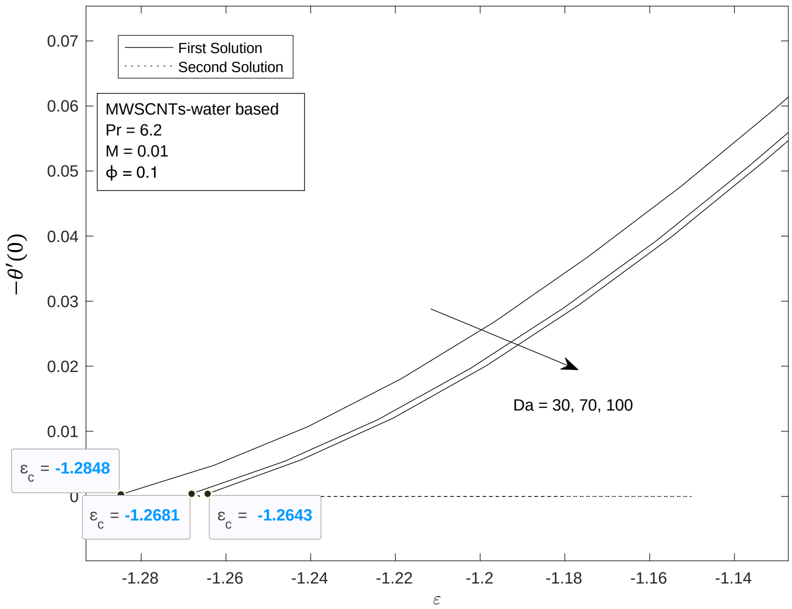

Fig. 5. Variation of $-\theta'(0)$ with different Da and ε for MWCNT-water based

To validate the numerical analysis for the thickness of boundary layer, the velocity fluid profile and the temperature profile are created for various values of M, Da and η both using SWCTS -water based and MWCNTs-water based as shown in Figure 6 to Figure 9. These figures are displaying a consistent result by showing that the boundary layer for second solutions is thicker than first solutions.

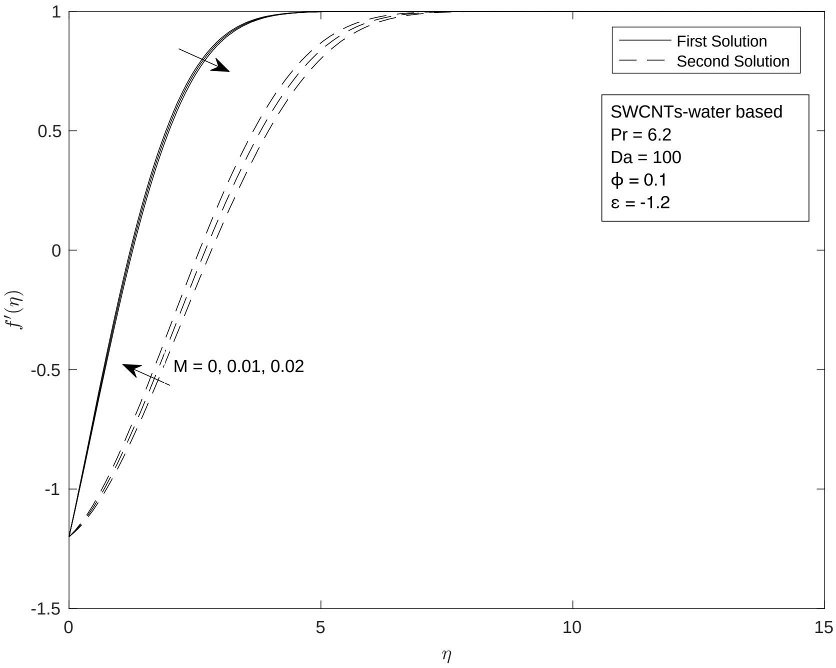

Fig. 6. Effect of different values of M on the velocity profile using various η and for SWCNT-water based

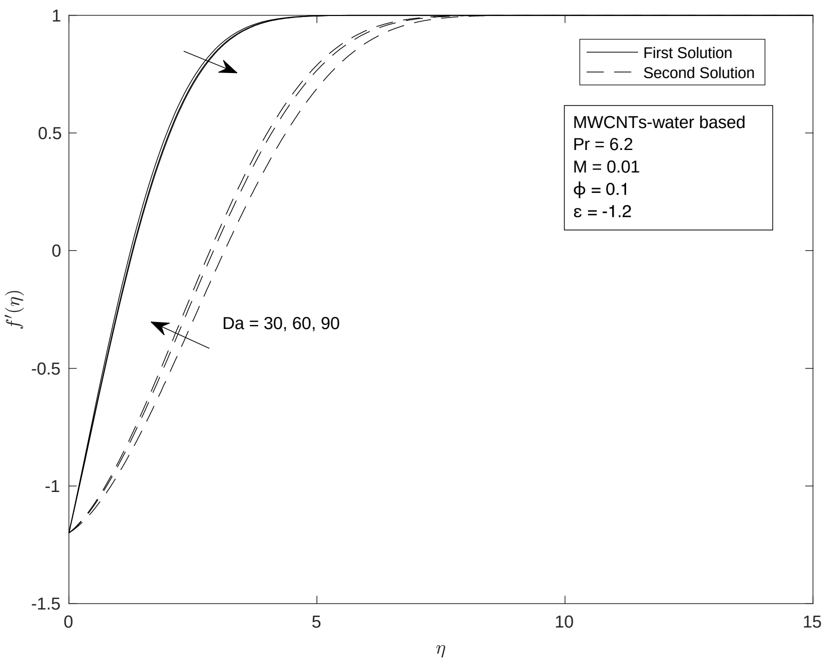

Fig. 7. Effect of different values of Da on the velocity profile using various η and for MWCNT-water based

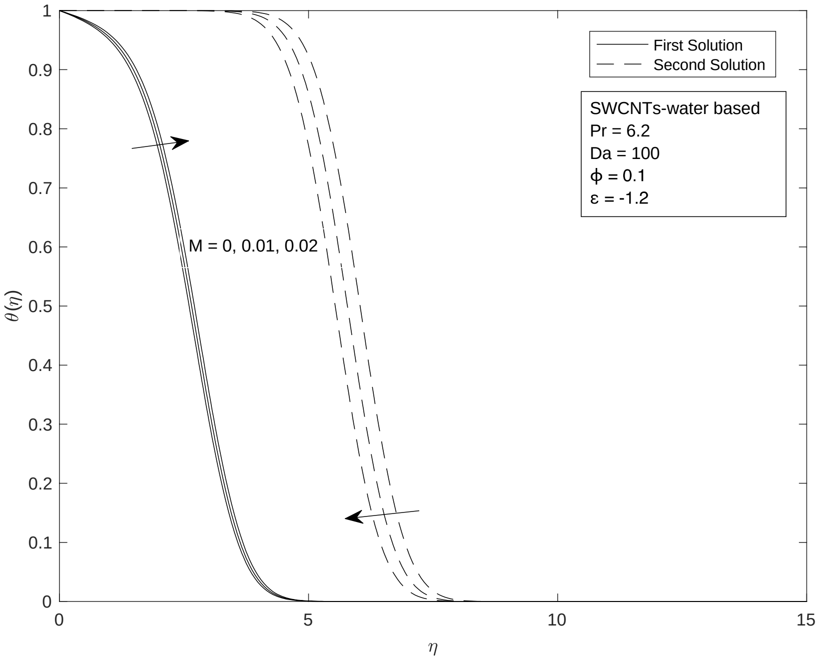

Fig. 8. Effect of different values of M on the temperature profile using various η and for SWCNT-water based

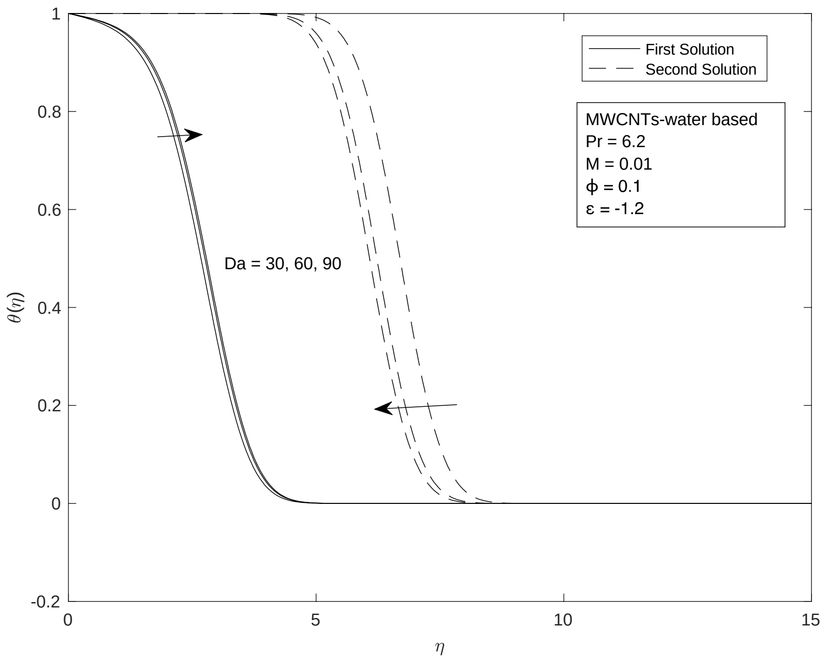

Fig. 9. Effect of different values of Da on the temperature profile using various η and for MWCNT-water based

Further analysis for the physical quantities of interest for the local skin friction and the local Nusselt number are explored through Figure 10 and Figure 11, respectively. The results are processed numerically for both SWCTs and MWCNTs in water by setting the variation values of ϕ, M (the investigation of the local skin friction coefficient), and Da (the investigation of the local Nusselt number) in intervals: $0 \leq \phi \leq 0.1$, M = 0, 0.1, 0.2 and Da = 1, 10, 100, respectively, while others parameters are kept at constant numbers. An increase of the local skin friction is reported when the value of M rises. On contrary, the local Nusselt number reduces as Da increases. Laboratory results proved that the decrease in heat transfer rate occurred due to additional flow resistance in porous medium as reported by Zhao *et al.,* [35]. Comparing the performance of SWCTs and MWCNTs in water, it can be seen that SWCTs are better than MWCNTs both in the local skin friction and the local Nusselt number. Besides, a linear increase is plotted if the ϕ increases both in $C_f\sqrt{Re_x}$ and $Nu_x/\sqrt{Re_x}$.

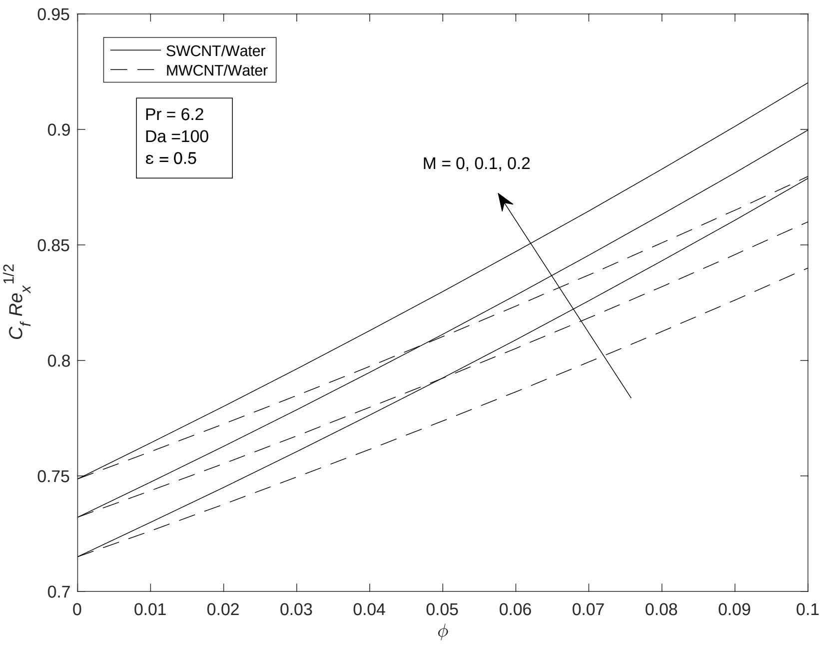

Fig. 10. Effect of different values of M on the skin friction coefficient using various ϕ for SWCNT-water based and MWCNT-water based

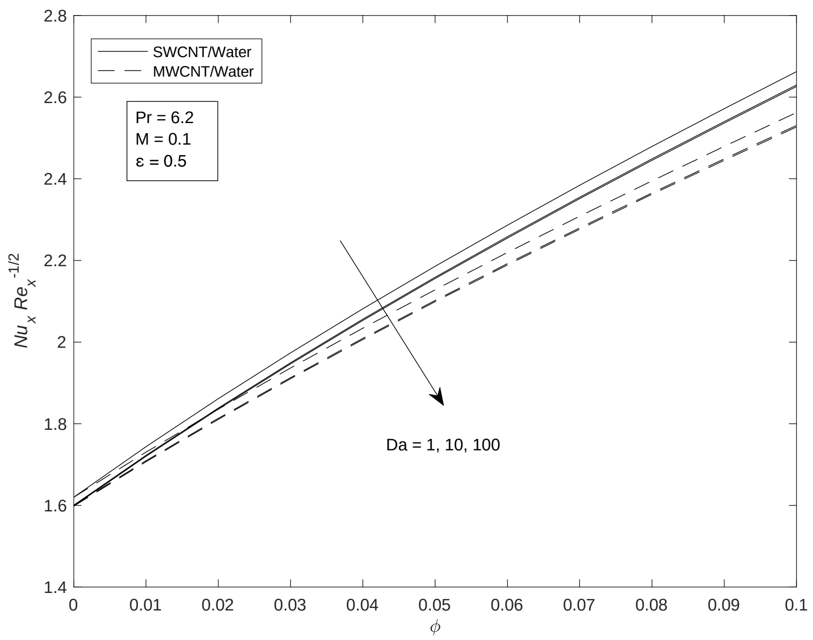

Fig. 11. Effect of different values of Da on the Nusselt Number using various ϕ for SWCNT-water based and MWCNT-water based

4. Conclusion

The boundary layer flow of CNTs nanofluids and heat transfer are analytically and numerically examined on the stagnation point flow across a stretching/shrinking sheet under the influence of porosity and hydromagnetic. The findings reveal that

i. Unique solutions for $f''(0)$ and $-\theta'(0)$ are generated when the sheet is stretched in the region of $\varepsilon > 0$ while duality of solutions is observed where $\varepsilon_c \leq \varepsilon \leq 0$ (shrunken sheet).
ii. The range of solutions for $f''(0)$ and $-\theta'(0)$ are shorten in the presence of high porosity, while magnetic field effect is expanding them.
iii. The increasing values of M and the decreasing values of Da promise increment both in the skin friction and the heat transfer.
iv. SWCNTs/water works better than MWCNTs/water due to higher thermal conductivity.

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