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HEAT TRANSFER EFFECTS ON CARBON NANOTUBES ALONG A MOVING FLAT PLATE SUBJECTED TO UNIFORM HEAT FLUX

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In the present paper, a theoretical analysis is made to investigate fluid flow and heat energy transformation features of single and multi-walled water functionalized carbon nanotubes (CNTs) with uniform heat inconstancy boundary conditions onward a flat plate. The liquid motion and momentum transfer of carbon nanotubes (CNTs) have been analyzed using a homogeneous flow model. Both single-wall CNTs (SWCNTs) and multi-wall CNTs (MWCNTs) used base fluids, namely, water. The thermophysical characteristics of CNTs regarding the solid volume fraction of CNTs are studied by applying empirical correlations. Similarity transformations have been used to the governing partial differential equations turning them into ordinary differential equations. The outcome of similarity transformations which are nonlinear ordinary differential equations subjected to reconstructed boundary conditions, are subsequently solved numerically using bvp4c. The effects of the governing parameters on the dimensionless velocity, temperature, and skin friction are investigated numerically and graphically. An increase in the volume fraction and the velocity ratio parameter increase the flow, the velocity, and the temperature profile. Regardless of any physical parameter, SWCNTs give better heat transfer than MWCNTs.

Keywords: SWCNTs, MWCNTs, heat transfer, bvp4c, similarity.

1. Introduction

It is necessary to improve the thermal conductivity of heat transfer fluids, as these fluids have many industrial applications in the heat exchangers, cooling systems, transport, and building sectors. Choi and Eastman [1] and Choi *et al*. [2] revealed that suspension containing ultrafine particles in nanofluid enhanced the rate of caloric conductivity. Adding CTN to the base fluid can significantly impact the thermo-physical properties. Many researchers have investigated the heat transfer characteristics of distinct nanofluid particles over distinctive geometries. Hone *et al*. [3], Liu *et al*. [4], Ding *et al*. [5], Garg *et al*. [6], Mintsa *et al*. [7], Ebrahimnia-Bejestan and Niazmand [8], Halelfadl *et al*. [9] and Sabiha *et al*. [10] proved experimentally that the caloric conductivity of energy mutated fluids can be amplified by *10-50%* surprisingly with microscopic rigid volume fraction of nanoparticles (conventionally smaller than *5%*). Eastman *et al*. [11] Trisaksri and Wongwises [12], Wang and Mujumdar [13], and Kakaç and Pramuanjaroenkij [14] reviewed these studies.

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Hone *et al*. [15], and Antar *et al*. [16] investigated the influence of single-wall CNT thermal conductivity up to $6600\ W/mK$ and multi-wall CNT thermal conductivity up to a hypothetical inquiry. An experimental investigation was carried out by Ding *et al*. [5] to observe the motion and the energy transfer characteristics of CNTs down a horizontal tube. A remarkable increment in the rate of heat transfer is observed, which relies on the Reynolds number and volume fraction of CNTs. Later, Kamali and Binesh [17] studied the heat transfer of MWCNT in a straight tube with wall heat mass flux conditions. Khan *et al*. [18] examined the heat transfer flow of carbon nanotube through the flat plate with Navier slip and heat flux boundary conditions. This work of Khan *et al*. [18] was extended by Anur *et al*. [19] to observe the stability analysis. Wang *et al*. [20] investigated the energy transfer and negative gradient of the pressure of CNTs in a flat circular tube experimentally. They showed that the Hagen-Poiseuille flow theory prediction validates the friction factor of diluted nanofluids. Said *et al*. [21] presented improved energy and exergy efficiency considering SWCNTs with spectroscopic technique.

Carbon nanotubes (CNTs) are noted to have particular caloric distinctive with very high thermal conductivities owing to cylindrical carbon molecule genesis. The CNTs have extents in micrometer and diameter from ~ 1 to $\sim 100\ nm$. Liu and Liang [22] invented an advance aqueous drag-shrinking flow with CNTs. This has ramifications of not only drag-contracting but also energy conduction increment. They performed assessments for investigating the imposed convective fluid and energy conduction behavior of typical drag-decreasing motion. Various differences in the heat transfer characteristics between both fluids were found, and the strong subordination of new nanofluid on the liquid temperature and the concentration of nanofluid and the cetyl trimethylammonium chloride was examined. The rate of convection of heat increment of aqueous suspensions of multi-walled CNTs passing through a linear horizontal tube was investigated experimentally by Mayer *et al*. [23]. They calculated some crucial terms concerning the Reynolds number, such as the energy transfer coefficient and the friction factors. The reason for increment was found while balancing the data on a Reynolds Nusselt graph; the consequence was that the shooting up of viscosity was four times the shooting up of the caloric conductivity. Various boundary surface motion problems regarding SWCNTs and MWCNTs have been reported recently [24-27].

The present article, influenced by the works mentioned above, is aimed to give a comprehensive insight into high thermal polymer processing. A mathematical model is developed for the fluid motion and caloric transformation features of single and multi-walled water-based CNTs along a horizontal plate subjected to a consistent gradient of heat boundary conditions. This model extends the earlier study of Khan *et al*. [18] to consider different parametric heat transfer effects. A nonlinear dimensionless ordinary differential boundary value problem is obtained by converting the partial differential boundary value problem by employing appropriate similarity transformations. A numerical solution is obtained with the bvp4c [28], and compared with Khan *et al*. [18]. A detailed parametric study and observation of the effect of volume fraction and velocity ratio parameter on velocity and temperature distributions are conducted with graphical visualization, along with the zoomed view of results and the skin friction profiles. The observed results may be constructive in understanding the complex interplay between volume fraction, slip parameter, and rheology in materials processing operations.

2. Problem formulation

We consider a two-dimensional laminar flow above a horizontal plate with heat momentum in water-based nanofluids restraining single- and multi-wall CNTs. We assume that the plate surface has a consistent heat gradient. The base fluids and the CNTs are in caloric balance. The no-slip hydrodynamic boundary condition between nanofluids and the horizontal facet is applied along with the dilapidation of the viscous dissipation and radiation results in the governing equation. The Cartesian coordinate system (Fig.1) has its origin located at the leading edge with the positive x-axis extending along with the sheet in the upward direction, while the y-axis is measured normal to the flow. The steady fluid and heat start with velocity U_0 along the x-axis. Keeping the origin fixed, T_w is the surface temperature, and T_∞ is the temperature outside the thermal boundary layer. The ambient temperature is assumed to be constant.

Under the boundary layer approximations, the continuity, the momentum, and the energy equations with variable thermal conductivity can be written as [18]:

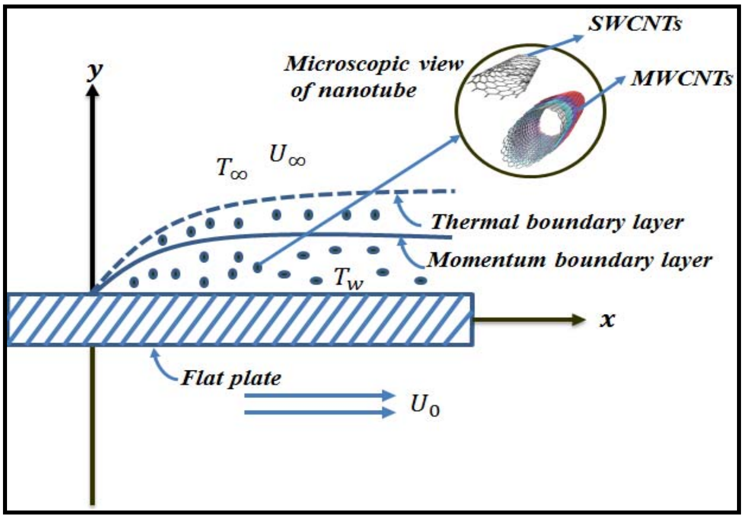

Fig.1. Flow problem.

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0. \tag{2.1}$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu_{nf}\frac{\partial^2 u}{\partial y^2}. \tag{2.2}$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\frac{\partial^2 T}{\partial y^2}. \tag{2.3}$$

Base fluid and carbon nanotubes help to examine the essential properties of nanofluids and the solid volume fraction of CNTs in the base fluids as follows:

$$\left.\begin{array}{ll}\rho_{nf}=(1-\phi)\rho_f+\phi\,\rho_{CNT}, & \mu_{nf}=\dfrac{\mu_f}{(1-\phi)^{2.5}},\\[2ex] \left(\rho C_p\right)_{nf}=(1-\phi)\left(\rho C_p\right)+\phi\left(\rho C_p\right)_{CNT}, & \nu_{nf}=\dfrac{\mu_{nf}}{\rho_{nf}},\end{array}\right\}. \tag{2.4}$$

where k_{nf} is the thermal conductivity of the nanofluid, $\left(\rho C_p\right)_{nf}$ is the thermal capacity of the nanofluid, and ϕ is the rigid volume fraction of the nanofluid.

The boundary conditions are as follows:

$$\left.\begin{array}{ll} u=U_0, \quad v=0, \quad -k\dfrac{\partial T}{\partial y}=q_w & at\ y=0, \\ & \\ u=U_\infty, \quad T=T_\infty & as\ y\rightarrow\infty \end{array}\right\} . \tag{2.5}$$

Here, U_∞ is the free stream velocity.

2.1. Effective thermal conductivity

Different researchers have proposed many theoretical models to predict the effective caloric conductivity increment of CNTs suspensions. All of these models were constructed with the help of Fourier's law of heat conduction. Maxwell [29] suggested the caloric conductivity ratio $=\dfrac{k_{CNT}}{k_f}$ can be expressed in terms of the effective caloric conductivity and the volume friction ϕ:

$$\frac{k_{CNT}}{k_f}=1+\frac{3(\alpha-1)\phi}{(\alpha+2)+(\alpha-1)\phi}. \tag{2.6}$$

Jeffery [30] and Davis [31] proposed the following theoretical models assuming higher orders of volume fraction,

$$\frac{k_{nf}}{k_f}=1+3\lambda\phi+\left(3\lambda^2+\frac{3\lambda^2}{4}+\frac{9\lambda^2}{16}\frac{\alpha+2}{2\alpha+3}+.....\right)\phi^2 \tag{2.7}$$

and

$$\frac{k_{nf}}{k_f}=1+\frac{3(\alpha-1)\phi}{(\alpha+2)+(\alpha-1)\phi}\left\{\phi+\phi(\alpha)\,\phi^2+O\left(\phi^3\right)\right\} \tag{2.8}$$

respectively, where, $\lambda=(\alpha-1)/(\alpha+2)$. The higher-order terms indicate a mutual relationship of a randomly dispersed sphere. But the shape factor of the particles cannot affect these models.
Hamilton and Crosser (1962) proposed that:

$$\frac{k_{nf}}{k_f}=\frac{\alpha+(n-1)-(n-1)(1-\alpha)\phi}{\alpha+(n-1)+(1-\alpha)\phi} . \tag{2.9}$$

Based on Maxwell's theory, Xue [32] developed a theoretical model where he considered rotational elliptical nanotubes with a huge axial ratio:

$$\frac{k_{nf}}{k_f}=\frac{1-\phi+2\phi\dfrac{k_{CNT}}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}}{1-\phi+2\phi\dfrac{k_f}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}}. \tag{2.10}$$

In our study, we have computed thermal conductivity and the dimensionless momentum rates of nanofluids using the Xue [32] model (see Eq.(2.10)). We will examine the skin friction and the dimensionless heat momentum of the nanofluid by developing a mathematical model. We will present the physical interpretation and significance of our results by solving the constructed model with a numerical approach.

2.2. Transformations

We first transform the boundary layer equations into a dimensionless system of equations using similarity variables. To simplify the governing equations, the similarity technique of coordinate transformation is used to reduce the number of independent variables. We have:

$$\left.\begin{aligned}&\psi=\nu\sqrt{\mathrm{Re}_x}\,f(\eta),\\ &\eta=\frac{y}{x}\sqrt{\mathrm{Re}_x},\\ &\theta(\eta)=\frac{T-T_\infty}{q_w x/k_f}\sqrt{\mathrm{Re}_x}\end{aligned}\right\}. \tag{2.11}$$

Thus, our final equations are:

$$\frac{1}{(1-\phi)^{2.5}\left\{1-\phi+\phi\dfrac{\rho_{CNT}}{\rho_f}\right\}}f'''+\frac{1}{2}f\,f''=0, \tag{2.12}$$

$$\frac{1}{\mathrm{Pr}}\frac{k_{nf}/k_f}{\left\{1-\phi+\phi\dfrac{(\rho C_p)_{CNT}}{(\rho C_p)_f}\right\}}\theta''+\frac{1}{2}(f\,\theta'-f'\theta)=0 \tag{2.13}$$

and the necessary conditions reduce to:

$$\left.\begin{aligned}&f(0)=0,\quad f'(0)=\lambda,\quad \theta'(0)=-\frac{k_f}{k_{nf}}\quad \text{at}\quad \eta=0,\\ &f'\to 1,\quad \theta\to 0\quad \text{as}\quad \eta\to\infty\end{aligned}\right\}. \tag{2.14}$$

where $\lambda = U_0 / U_\infty$ is the velocity ratio parameter. The plate moves in the assisting flow if $\lambda > 0$, and the plate moves in the opposing flow if $\lambda < 0$ and $\Pr = \left(\mu C_p\right)_f / k_f$ is the Prandtl number of the base fluid.

3. Numerical procedure

The coupled nonlinear ordinary differential equations (2.12) and (2.13) along with the boundary conditions (2.14) for the Prandtl number Pr, the CNT volume fraction ϕ, and the velocity ratio parameter λ, are solved using a finite difference method as well as a shooting technique. The boundary value problem was transformed into an initial value problem, which was solved by systematic guessing for $f''(0)$ and $\theta'(0)$ until the necessary constraints have been at ∞, asymptotically converging to zero. To secure the convergence in each case, the step size $\Delta\eta = 0.001$ is utilized to acquire the numerical solution with $\eta_{\max} = 8$.

4. Graphical representation, results and discussion

A water-based fluid has been used to examine the flow and heat motion rate of single- and multi-wall CNTs. A set of nonlinear equations is solved numerically after transforming them from the governing PDE along with the necessary boundary conditions. In Tab.1, the thermophysical properties of water and both CNTs are shown.

Table 1. Thermophysical properties of water-based fluid and both CNTs [18].

Physical properties	Base fluid	Nanoparticles	
	Water	SWCNT	MWCNT
$\rho\left(kg/m^3\right)$	*997*	*2600*	*1600*
$C_p\ (J/kg\ K)$	*4179*	*425*	*796*
$k\ (W/m\ K)$	*0.613*	*6600*	*3000*

Table 2. Variation of the thermophysical properties with volume fraction of both CNTs.

SWCNT	ϕ	ρ	$\rho C_p (\times 10^6)$	k
Water	*0*	*997*	*4.167*	*0.613*
	0.04	*1061*	*4.044*	*1.051*
	0.08	*1125*	*3.921*	*1.528*
	0.12	*1189*	*3.799*	*2.048*
	0.16	*1253*	*3.676*	*2.618*
	0.2	*1317*	*3.554*	*3.245*
MWCNT	ϕ	ρ	$\rho C_p (\times 10^6)$	k
Water	*0*	*997*	*4.167*	*0.613*
	0.04	*1021*	*4.051*	*1.011*
	0.08	*1045*	*3.935*	*1.444*
	0.12	*1069*	*3.819*	*1.916*
	0.16	*1093*	*3.703*	*2.434*
	0.2	*1117*	*3.588*	*3.002*

Table 2 presents the variation of the caloric patterns of the water-based nanofluids with rigid volume portions of single- and multi-wall CNTs. It is observed that the density and the thermal conductivity are proportional, and the heat capacity is inversely proportional to the rigid volume portion for each CNT. To examine the accuracy of our computational method, we have compared our results for the skin friction and local Reynolds number for water-based SWCNT and MWCNT with those of Khan *et al*. [18], as shown in Tab.3. The results are found to be in excellent agreement with the published data.

Table 3. Comparison of the values of skin friction with $\lambda = 0$ and no-slip conditions with Khan *et al*. results [18].

Case	ϕ	$\mathrm{Re}_x^{1/2}\, C_f$	
		Khan *et al.* [18]	Present
Water-based SWCNT	0.01	0.33894	0.338942
	0.1	0.40811	0.408110
	0.2	0.50452	0.504521
Water-based MWCNT	0.01	0.33727	0.337268
	0.1	0.39008	0.390076
	0.2	0.46466	0.464659

We have used the graphical method to consider the effects of various parameters on the flow profile, the velocity profile, and the temperature profile. We have represented the flow profile, the velocity profile, and the temperature profile considering the changes in the volume fraction ϕ and velocity ratio parameter λ. The results are discussed below.

The effects of the volume fraction ϕ on the flow profile

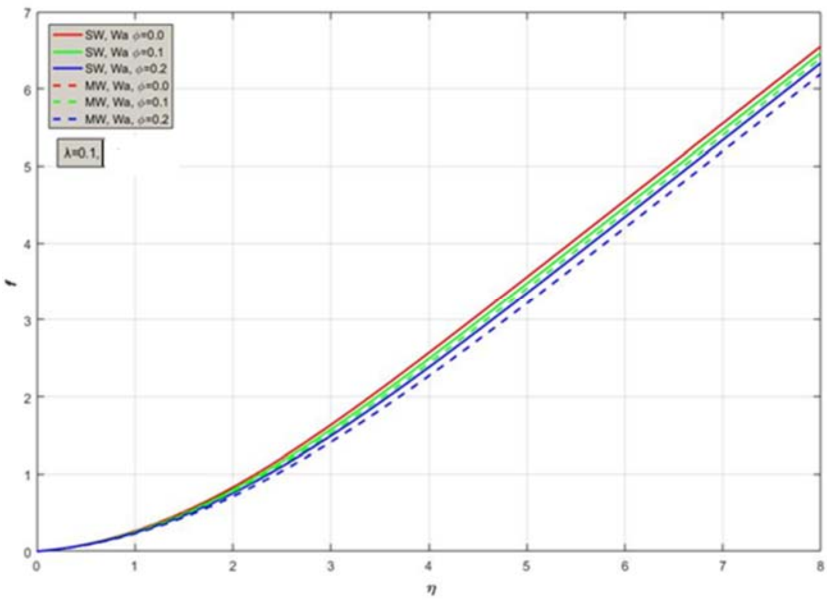

Fig.2. Flow profile corresponding to ϕ.

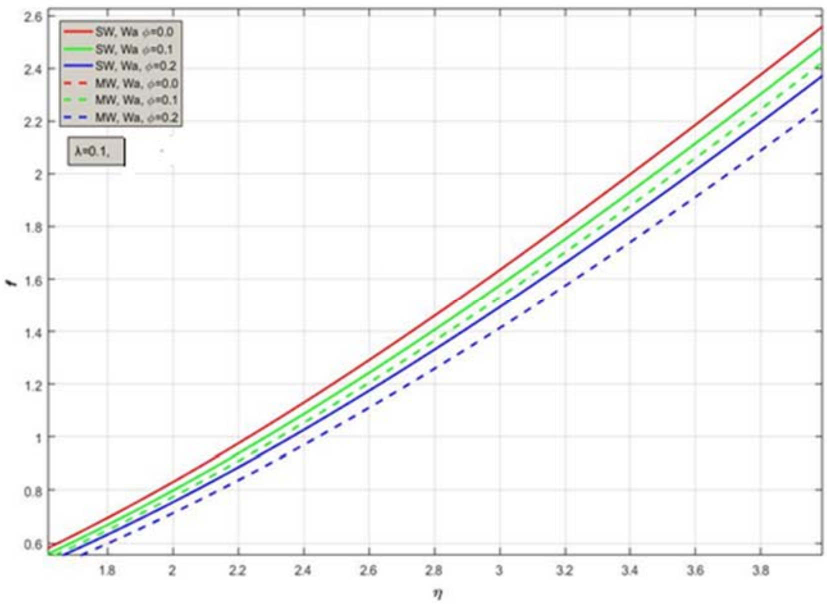

Fig.3. Zoomed preview of the flow profile.

Figure 2 shows the effects of the nanoparticle volume fraction on the flow profile for the water-based SWCNTs and MWCNTs. The case of pure fluid $(\phi = 0)$ is also studied to compare the pure fluid flow with the nanofluid flow. It can be observed that the flow increases with the volume fraction of each CNTs. Hence it can be concluded that with an increase in nanoparticle volume fraction for a particular case, the flow profiles for SWCNT are higher than MWCNT for water. For clarity, we have also represented a zoomed preview of the flow in Fig.3.

The effect of the volume fraction ϕ in the velocity profile

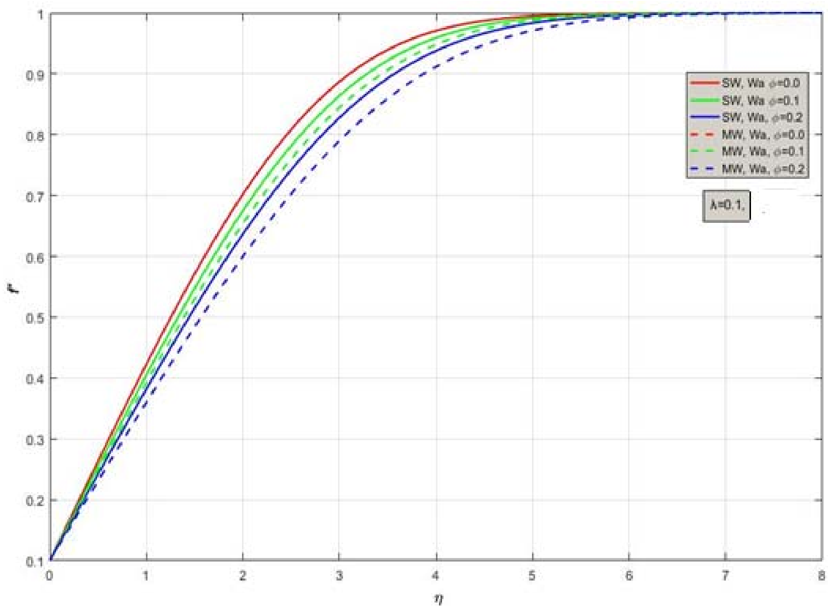

Fig.4. Velocity profile corresponding to ϕ.

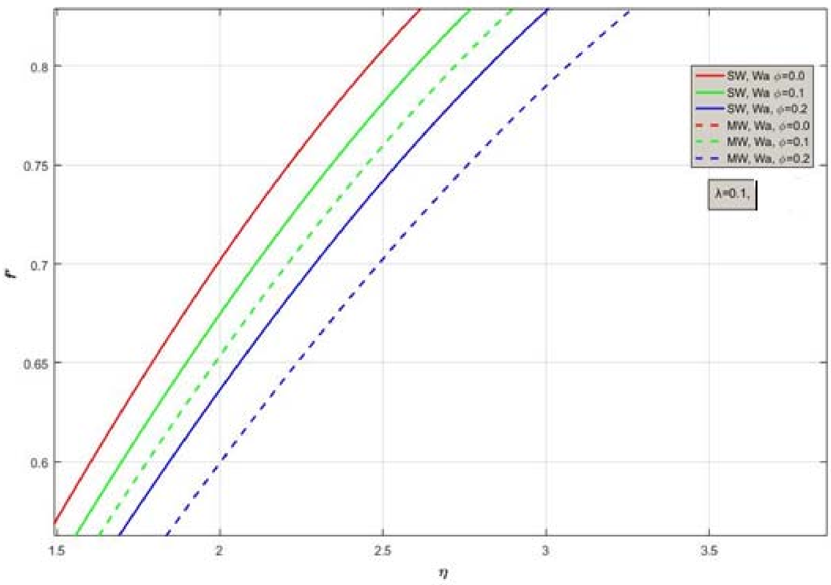

Fig.5. Zoomed preview of the velocity profile.

The influence of the nanoparticle volume fraction parameter ϕ on the velocity profile in water-based SWCNTs and MWCNTs is shown in Fig. 4. The case of pure fluid $(\phi = 0)$ is also studied to compare the pure fluid velocity flow with nanofluid velocity flow. It can be observed that the velocity profile increases with the volume fraction of each CNTs. It can also be observed that with an increase in the nanoparticle volume fraction for a particular case, the velocity flow profiles for SWCNT are higher than MWCNT for water-based nanofluids. For clarity, we have also represented a zoomed preview of the velocity profile in Fig.5.

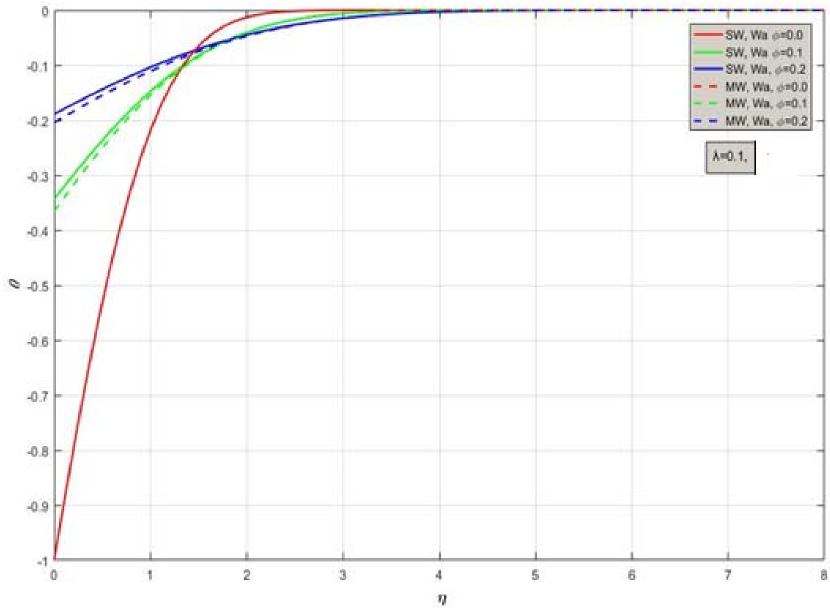

Fig.6. Temperature profile corresponding to ϕ.

The effects of the volume fraction ϕ on the temperature profile

The effects of the nanoparticle volume fraction parameter ϕ of both CNTs on the temperature profile are illustrated in Fig.6. It can be observed that with an increase in the nanoparticle volume fraction for a particular case, the temperature profiles for SWCNTs are higher than MWCNTs for water-based nanofluids. For clarity, we also have represented a zoomed preview of the temperature profile in Fig.7.

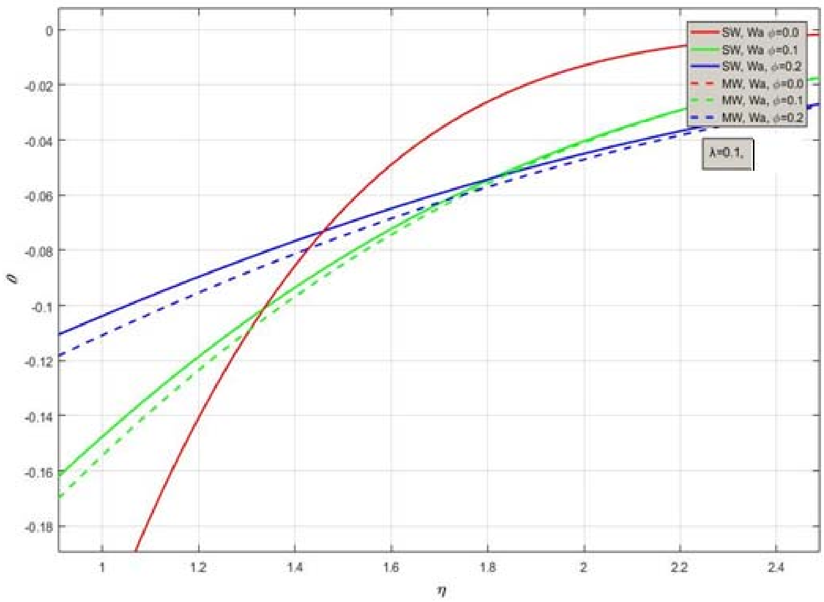

Fig.7. Zoomed preview of the temperature profile.

The effect of the velocity ratio parameter λ on the flow profile:

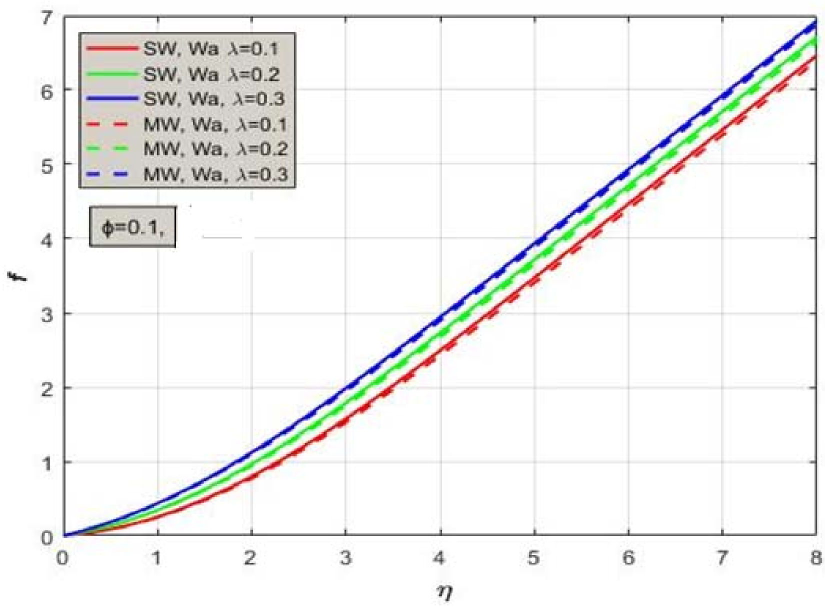

Fig.8. Flow profile corresponding to λ.

The effects of the velocity ratio parameter λ on the flow profile in the presence of water-based SWCNTs and MWCNTs are shown in Fig.8. It can be seen that the flow profile increases with the velocity ratio parameter of each CNTs. It can also be observed that with an increase in the velocity ratio parameter for a particular case, the flow profiles for SWCNTs are higher than MWCNTs for any fluid. A zoomed preview of the flow is shown in Fig.9 for clarity.

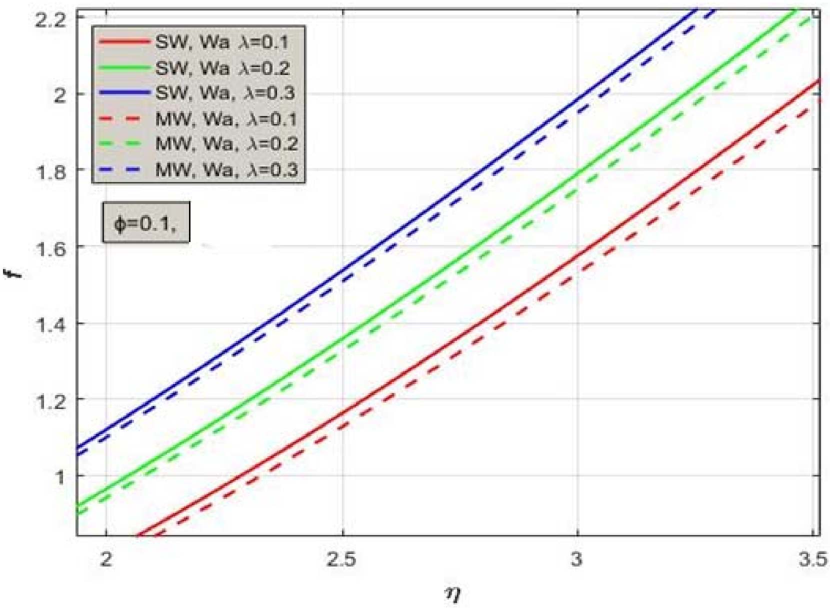

Fig.9. Zoomed preview of the flow profile.

The effects of the velocity ratio parameter λ on the velocity profile

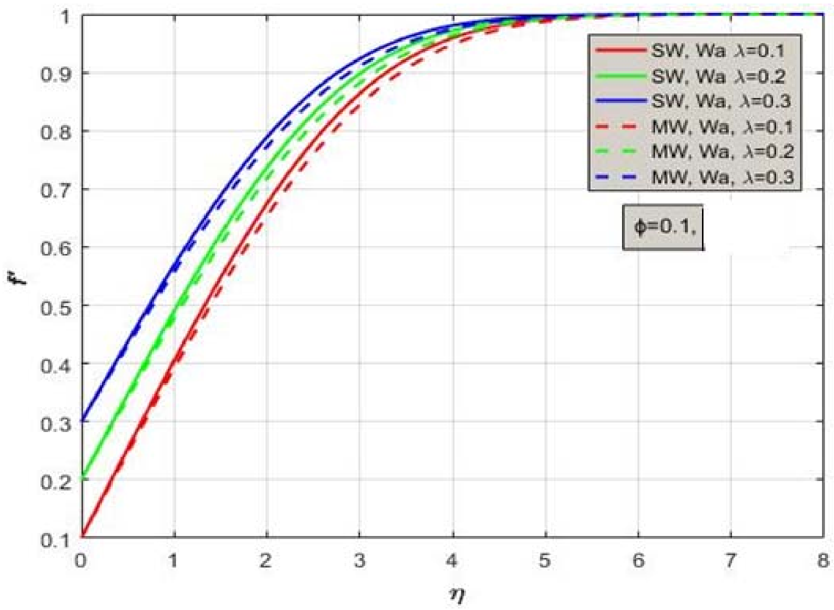

Fig.10. Velocity profile corresponding to λ.

Figure.10 shows the effects of the velocity ratio parameter λ on the velocity profiles for water-based nanofluids SWCNTs and MWCNTs. It can be seen that the velocity increases with the velocity ratio parameter.

With an increase in the velocity ratio parameter for a particular case, the velocity profiles for SWCNTs are higher than MWCNTs. For clarity, a zoomed preview of the velocity is shown in Fig.11.

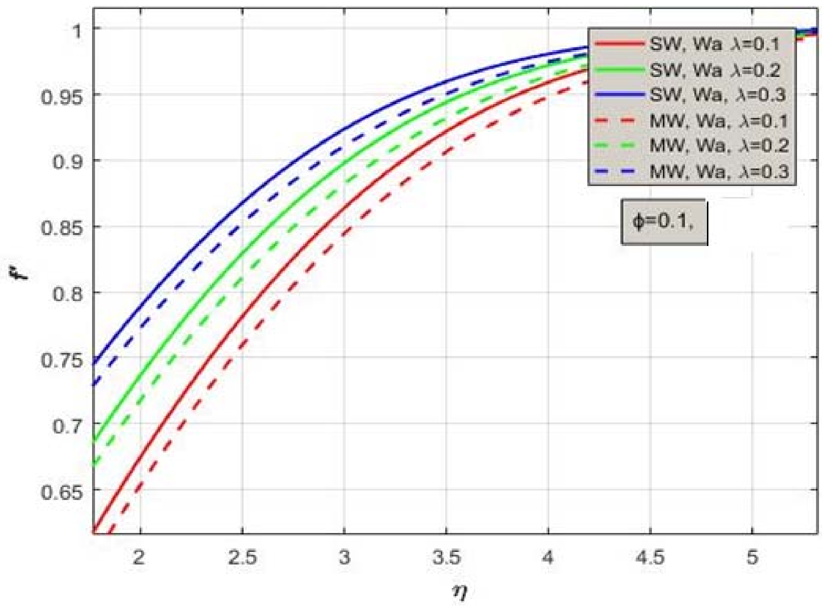

Fig.11. Zoomed preview of the velocity profile.

The effects of the velocity ratio parameter on the temperature profile

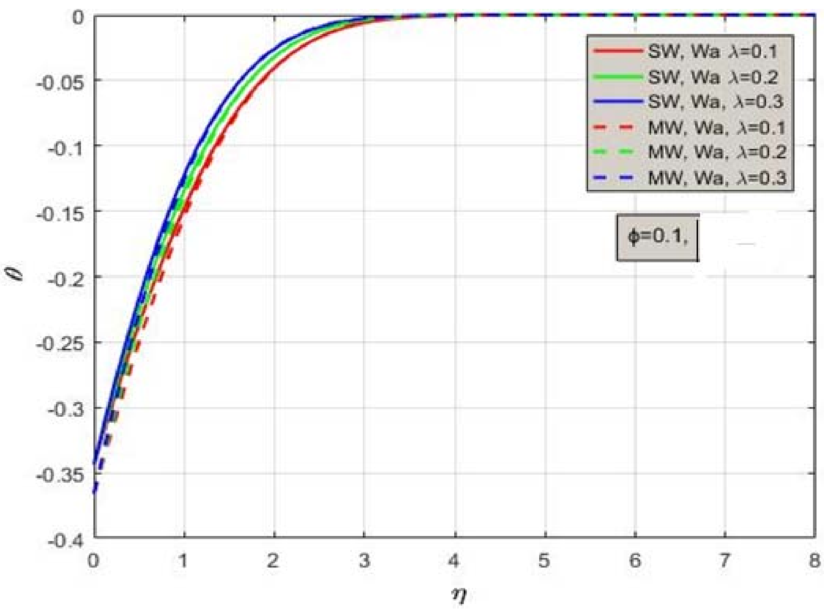

Fig.12. Temperature profile corresponding to λ.

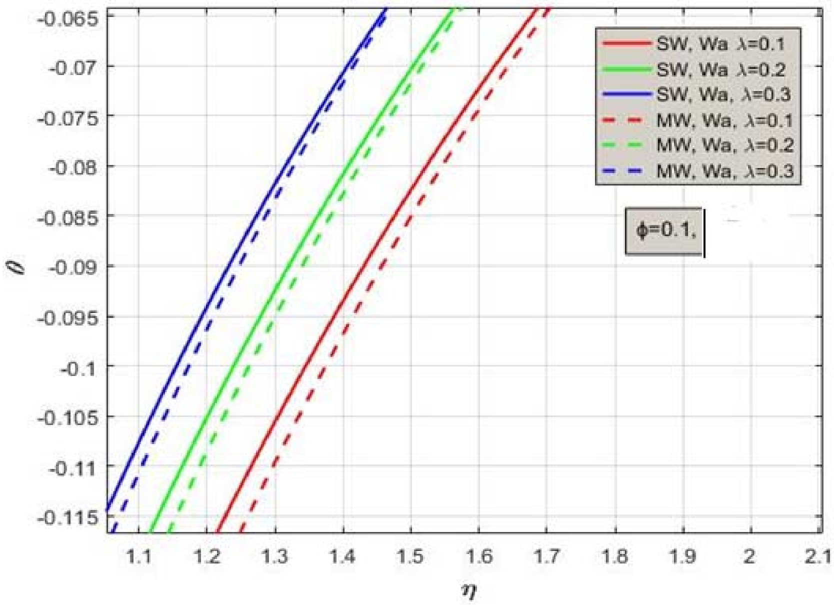

Fig.13. Zoomed preview of the temperature profile.

Figure 12 shows the effects of the velocity ratio parameter λ, on the temperature distribution in the presence of water-based SWCNTs and MWCNTs. It is observed that the temperature increases with an increase in the velocity parameter. It also can be observed that with an increase in the velocity ratio parameter the temperature distributions for SWCNTs are higher than MWCNTs. For clarity, we have also represented a zoomed preview of the temperature flow in Fig.13.

5. Conclusion

A numerical solution of the two-dimensional flow of fluid and heat transfer features of single and multi-walled water-based functionalized CNTs along a flat plate subjected to Navier slip and uniform heat flux boundary conditions has been discussed in the present analysis. The consequences of various parameters, that govern the flow phenomena are presented graphically using ***'bvp4c'*** in ***'Matlab'*** with an accuracy of 10^{-6}. The effects of the governing parameters on the flow, velocity, and temperature were studied, and the following conclusions were made:

- Volume fraction positively affects the flow, velocity, and temperature distribution.
- The flow, velocity, and temperature profiles increase with an increase in the velocity ratio parameter.
- Temperature distribution increases with an increase of all governing parameters.
- Temperature exponent enhances the rate of heat transfer.
- Regardless of any physical parameter, SWCNTs give better heat transfer than MWCNTs.

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Nomenclature

C_p – specific heat at constant pressure

f – dimensionless stream function
k – thermal conductivity
n – shape factor
Pr – Prandtl number
Re_x – local Reynolds number
T – local fluid temperature
T_w – temperature of the surface
T_∞ – free stream temperature
(u, v) – velocity components
U_0 – initial fluid velocity
U_∞ – free stream velocity
(x, y) – components of the cartesian system
α – thermal diffusivity
η – similarity variable
θ – dimensionless temperature
ρ – fluid density
υ – kinematic viscosity
λ – velocity ratio parameter
μ – absolute viscosity
φ – volume fraction
ψ – stream function

Abbreviations

CNT – carbon nanotube
SWCNT – single-wall carbon nanotube
MWCNT – multi-wall carbon nanotube

Subscripts

$(\ )_{nf}$ – nanofluid
$(\ )_f$ – base fluid
$(\ )_{CNT}$ – carbon nanotube

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