SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

CFD Letters

Journal homepage:
https://semarakilmu.com.my/journals/index.php/CFD_Letters/index
ISSN: 2180-1363

Dusty Casson Fluid Flow containing Single-Wall Carbon Nanotubes with Aligned Magnetic Field Effect over a Stretching Sheet

Nur Syamilah Arifin[1,*], Abdul Rahman Mohd Kasim[2], Syazwani Mohd Zokri[3], Siti Farah Haryatie[4], Mohd Zuki Salleh[2]

[1] Fakulti Sains Komputer & Matematik, Universiti Teknologi MARA, Cawangan Johor, Kampus Pasir Gudang, 81750, Masai, Johor, Malaysia
[2] Pusat Sains Matematik, Universiti Malaysia Pahang, 26300, Gambang, Pahang, Malaysia
[3] Fakulti Sains Komputer & Matematik, Universiti Teknologi MARA, Cawangan Kuala Terengganu, Kampus Kuala Terengganu, 21080, Kuala Terengganu, Malaysia
[4] Fakulti Sains Komputer & Matematik, Universiti Teknologi MARA, Cawangan Kelantan, Kampus Machang,18500, Kelantan, Malaysia

ARTICLE INFO

Article history:
Received 6 September 2022
Received in revised form 28 September 2022
Accepted 22 October 2022
Available online 1 January 2023

Keywords:
Dusty Casson nanofluid; SWCNTs; Aligned magnetic field; Newtonian Heating

ABSTRACT

Two-phase flow is the mutual interaction between solid and fluid phases which encountered in real life applications, such as sedimentation, blood flow, water pollution, fluidized bed and to name a few. In the theoretical study, this binary mixture is represented by partial differential equations that denotes its physical properties of all phases. Therefore, the interaction between three important elements over a stretching sheet is examined in this study where the focus is on Casson fluid, single-wall carbon nanotubes (SWCNTs) and dust particles. Moreover, the aligned magnetic field effect and Newtonian heating (NH) are associate together to influence the flow region. In order to generate the results, the equations that governed the current model must therefore employ the similarity variables to produce the ordinary differential equations. Formulation of the problem is then continued by solving the resulting equations using Runge-Kutta Fehlberg (RKF45) method. Significant outputs for considered parameters are presented through graph. It is found that, the growing effect of fluid-particle interaction particle decreases the fluid phase distribution which contributes to the opposite trend in dust phase.

1. Introduction

The theoretical study on fluid flow and heat transfer containing particles has been explored by many authors due to the advancement in the engineering, medical, industrial, technology and others applications. To meet these demands, researchers are motivated to introduce several models in dissimilar circumstances which simulate the physical situation in those applications into mathematical equations by considering certain assumptions. Two-phase flow model is one of the proposed models that can be used to measure the distributions of fluid and particles simultaneously, which is valid for spherical particles. It has been introduced to improve the conventional model shortcomings as the focus is solely on fluid flow. Saffman [1] pioneered the investigation of dust

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[*] *Corresponding author.*
E-mail address: nursyamilaharifin@uitm.edu.my (Nur Syamilah Arifin)

https://doi.org/10.37934/cfdl.15.1.1725

particles in the motion of a gas in which the governing equations for each phase have been presented in his reported work. Many researchers followed the lead, and the exploration on this particular model thenceforth extensively increased for the flow problems with various conditions. Abbas *et al.,* [2] carried out the study on Newtonian fluid flow containing dust particles through porous medium associated with magnetic field and slip effects. On the other hand, a comprehensive literature review on the growth of two-phase model concerning non-Newtonian fluid as a base fluid is reported by Aljabali *et al.*, [3] and in the subsequent years, they continued to analyse Erying Powell fluid flow with the impact of temperature-dependent viscosity [4, 5]. Some recent investigations associated with two-phase flow problems for various non-Newtonian fluid in different geometries have been conducted by several authors [6-10].

Besides, there is also numerous research activities on the suspension of particles in fluid or can be recognized as nanofluid. However, the particles are in nanometer-sized and made up from various materials such as metals alumina, copper, metal oxides, Carbonxymethyl cellulose (CMC), carbon nanotubes (CNTs) and to name a few. As for base fluid, it allows for any types of Newtonian and non-Newtonian fluids. Choi and Eastman [11] conclude that the adding of nanoparticles significantly increase the heat flow of fluid which can benefit many industrial applications. Such nanoparticles are important in solar receiver, nuclear, biomedical applications, heat exchanger, thermal storage and industrial cooling medium [12]. Alwawi *et al.*, [13] addressed about the magnetic field effect on combined flow of free and forced convections over a solid sphere with copper, aluminum and silver nanoparticles by considering Casson fluid. Furthermore, a considerable amount of published works on distinct types of non-Newtonian fluid flow with nanoparticles have been explored in several studies [14-18]. Along with the development in nanotechnology field, exploration on this matter came into the limelight that renders the researchers to further investigate the thermo-physical characteristics of nanoparticles. One of them is CNTs, a cylinder tubes composed of carbon atoms, which has been proved to possess a remarkable thermal conductivity. Generally, there are two categories currently being investigated in research into CNTs: single-wall carbon nanotubes (SWCNTs) and multiple-wall carbon nanotubes (MWCNTs). Both CNTs have been examined by several authors whereby they reached a conclusion that SWCNTs have higher heat competency as compared to MWCNT [19, 20]. Thus, this paper will examine the significance of SWCNTs on the flow region. An analytical work on magnetic field flow problem of nanofluid filled with CNTs for varying conditions has been carried out by Aman *et al.,* [20], Saqib *et al.,* [21] and Hussanan *et al.,* [22]. Recent contributions on CNTs have been treasured in the existing literature [23–26].

From the abovementioned works, it can be noticed that the fluid flow problems containing dust particles and nanoparticles are solved independently. Attempts to account for the existence of both particles in fluid motion are worthy of special treatment and to the best of our knowledge, there are few studies conducting on their interaction especially for CNTs case. Other than that, the rheological behaviour of non-Newtonian Casson fluid is said to closely resemblance human blood as compared to others models [27]. By taking these into accounts, this paper examines the addition of SWCNTs in human blood flow by introducing magnetic field impact and Newtonian heating (NH) on flow region. Note that, human blood is assumed as fluid-solid particle system, whereby Casson fluid and dust particles represent the fluid and dust phases, respectively. Numerical computation of the present model is carried by employing RKF45 method and is displayed in graphical form.

2. Mathematical Model

A steady, two dimensional and incompressible flow of Casson fluid embedded with SWCNTs and spherical shape with constant dimension of dust particles under the influenced of modified magnetic field effect is conducted here. The stretching sheet is assumed to move with constant velocity, $u_w(x)$, as displayed in Figure 1 where vertical line represents x- axis and y- axis normal to it.

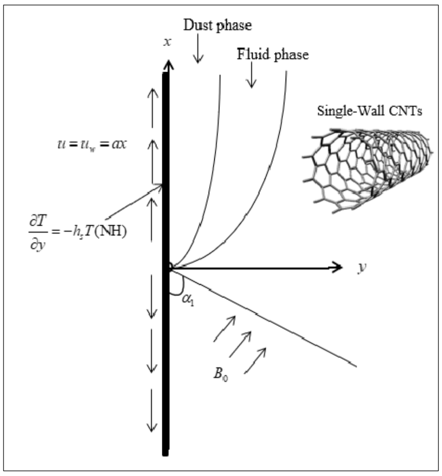

Fig. 1. Physical model of two-phase flow

The governing equation of the motion and heat transfer of current problem can be described as below [28, 29]

Casson fluid phase:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\mu_{nf}}{\rho_{nf}}\left(1+\frac{1}{A}\right)\left(\frac{\partial^2 u}{\partial y^2}\right) + \frac{\rho_p}{\rho_{nf}\tau_v}(u_p - u) - \frac{\sigma_{nf}}{\rho_{nf}} u {B_0}^2 \sin^2\alpha_1, \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{\left(\rho c_p\right)_{nf}}\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{\rho_p c_s}{\left(\rho c_p\right)_{nf}\tau_T}(T_p - T), \tag{3}$$

Dust particle phase:

$$\frac{\partial}{\partial x}(u_p) + \frac{\partial}{\partial y}(v_p) = 0\,, \qquad 4)$$

$$u_p\frac{\partial u_p}{\partial x} + v_p\frac{\partial u_p}{\partial y} = \frac{1}{\tau_v}(u - u_p), \tag{5}$$

$$u_p\frac{\partial T_p}{\partial x} + v_p\frac{\partial T_p}{\partial y} = -\frac{1}{\tau_T}(T_p - T)\,, \tag{6}$$

where $\left(u,v\right)$, T, ρ_{nf}, $\left(c_p\right)_{nf}$, μ_{nf}, σ_{nf}, α_1 and B_0 are the velocity components in $\left(x,y\right)$ directions, temperature, density, specific heat at constant pressure, plastic dynamic viscosity of non-Newtonian, electrical conductivity, aligned angle and magnetic field for fluid phase, respectively. $\left(u_p,v_p\right)$, T_p, ρ_p c_s, τ_v and τ_T denote the velocity components in $\left(x,y\right)$ directions, temperature, density, specific heat, velocity and thermal relaxation time for dust phase, respectively. The thermophysical properties of nanofluid and nanoparticles are listed in Tables 1 and 2 where subscript f, CNT and ϕ correspond to fluid, carbon nanotubes and solid volume fraction of nanoparticles.

Table 1
Thermophysical properties of nanofluid

Properties	Nanofluid
Density	$\rho_{nf}=\left(1-\phi\right)\rho_f+\phi\rho_{CNT}$
Heat capacity	$\left(\rho c_p\right)_{nf}=(1-\phi)\left(\rho c_p\right)_f+\phi\left(\rho c_p\right)_{CNT}$
Dynamic viscosity	$\mu_{nf}=\dfrac{\mu_f}{\left(1-\phi\right)^{2.5}}$
Thermal diffusivity	$\alpha_{nf}=\dfrac{k_{nf}}{\left(\rho c_{cp}\right)_{nf}}$
Thermal conductivity	$\dfrac{k_{nf}}{k_f}=\dfrac{(1-\phi)+2\phi\dfrac{k_{CNT}}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}}{(1-\phi)+2\phi\dfrac{k_f}{k_{CNT}-k_f}\ln\dfrac{k_{CNT}+k_f}{2k_f}}$
Electric conductivity	$\dfrac{\sigma_{nf}}{\sigma_f}=1+\dfrac{3\left(\dfrac{\sigma_{CNT}}{\sigma_f}-1\right)\phi}{\left(\dfrac{\sigma_{CNT}}{\sigma_f}+2\right)-\left(\dfrac{\sigma_{CNT}}{\sigma_f}-1\right)\phi}$

Table 2
Thermophysical properties of fluid and nanoparticles [27]

Physical Properties	Based fluid	Nanoparticles
	Human blood	SWCNTs
ρ (kg/m^3) A	1053	2600
C_p (J/kgk) B	3594	425
k (W/mk) C	0.492	6600
σ (s/m) D	0.18	10^6 - 10^7

Eqs. (1)-(6) obey the following flow and thermal boundary conditions

$$
\begin{aligned}
&u=u_w(x)=ax,\ \ v=0,\ \ \frac{\partial T}{\partial y}=-h_sT\ \text{ at }\ y=0,\\
&u\to 0,\ \ u_p\to 0,\ \ v_p\to v,\ \ T\to T_\infty,\ \ T_p\to T_\infty\ \text{ as }\ y\to\infty.
\end{aligned}
\tag{7}
$$

where h_s represents heat transfer coefficient. Similarity variables under consideration are

$$\begin{aligned} &u = axf'(\eta),\ \ v = -\left(a\upsilon\right)^{1/2} f(\eta),\ \ \eta = \left(\frac{a}{\upsilon}\right)^{1/2} y,\ \ \theta(\eta) = \frac{T - T_\infty}{T_\infty}, \\ &u_p = axF'(\eta),\ \ v_p = \left(a\upsilon\right)^{1/2} F(\eta),\ \ \theta_p(\eta) = \frac{T_p - T_\infty}{T_\infty}, \end{aligned} \tag{8}$$

Solving the governing equations by applying Eq. (8) results to

$$\frac{\mu_{nf}/\mu_f}{\rho_{nf}/\rho_f}\left(1+\frac{1}{A}\right) f'''(\eta) + f(\eta) f''(\eta) - \left(f'(\eta)\right)^2 + \frac{\beta N}{\rho_{nf}/\rho_f}\left(F'(\eta) - f'(\eta)\right) - \frac{\sigma_{nf}}{\sigma_f} M \sin^2 \alpha_1 f'(\eta) = 0, \tag{9}$$

$$\frac{k_{nf}}{k_f}\theta''(\eta) + \Pr\left(\frac{\left(\rho c_p\right)_{nf}}{\left(\rho c_p\right)_f}\right) f(\eta)\theta'(\eta) + \frac{2}{3}\beta N\left(\theta_p(\eta) - \theta(\eta)\right) = 0, \tag{10}$$

$$\left(F'(\eta)\right)^2 - F(\eta)F''(\eta) + \beta\left(F'(\eta) - f'(\eta)\right) = 0, \tag{11}$$

$$\theta_p{}'(\eta)F(\eta) + \frac{2}{3}\frac{\beta}{\Pr\gamma}\left(\theta(\eta) - \theta_p(\eta)\right) = 0\,. \tag{12}$$

The model is bounded by the following equations

$$\begin{aligned} &f(0) = 0,\ \ f'(0) = 1,\ \ \theta'(0) = -b\left(1+\theta(0)\right)\ \text{ at }\ \eta = 0 \\ &f'(\eta) \to 0,\ F(\eta) \to 0,\ F(\eta) \to f(\eta),\ \theta(\eta) \to 0,\ \theta_p(\eta) \to 0\ \text{ as }\ \eta \to \infty \end{aligned} \tag{13}$$

where

$$A = \mu_B\frac{\sqrt{2\pi_c}}{\rho_y},\ N = \frac{\rho_p}{\rho},\ M = \frac{\sigma B_0^2}{\rho a},\ \beta = \frac{1}{a\tau_v},\ \ \Pr = \frac{\mu c_p}{k},\ \gamma = \frac{c_s}{c_p},\ b = -h_s\left(\frac{\nu}{a}\right)^{\frac{1}{2}}, \tag{14}$$

represent Casson parameter, mass concentration of particle phase, magnetic field parameter, fluid-particle interaction parameter, Prandtl number, specific heat ratio of mixture and conjugate parameter for NH, respectively. Furthermore, if M and β are not addressed in this study, the exact equation for single-phase flow of Casson fluid can be acquired. Thus, Eq. (9) results to the following equation

$$f(\eta) = \left(1+\frac{1}{A}\right)^{1/2}\left(1 - \exp\left(-\frac{\eta}{\left(1+1/A\right)^{1/2}}\right)\right). \tag{15}$$

The physical quantities on the surface sheet for the current model are

$$C_f \mathrm{Re}_x^{1/2} = \frac{1}{(1-\phi)^{2.5}}\left(1+\frac{1}{A}\right) f''(0), \quad Nu_x \mathrm{Re}_x^{-1/2} = b\left(\frac{1}{\theta(0)}+1\right). \tag{16}$$

3. Results

In this section, the mathematical analysis of the present flow is discussed in details. The solutions for assorted values of ϕ and β are computed by setting $\mathrm{Pr} = 21, A = 1, M = 2, \alpha_1 = \pi/6$, $N = \beta = 0.5$, $\phi = 0.01$ and $b = 0.3$. To guarantee the exactness of current solutions, the current model is compared with analytic solution obtained from Eq. (15) and existing numerical work carried out by Nadeem *et al.,* [30] using RKF45 method. It is conducted by transforming the current model into conventional model by ignoring certain parameters. From Table 3, an excellent agreement of $C_f Re_x^{1/2}$ for several values of A can be noticed which indicate that the obtained results are considered to be accurate. Next, exploration in the behaviour of all phases for the involved parameters is carried out through graphical form.

Figures 2 to 5 show the behaviour of flow and heat transfer of all phases to the influence of parameters ϕ and β. Both profiles of fluid phase are observed to reduce as β enhances. However, dust phase experiences increasing trend in all profiles. This result is attributed to the reduction of the velocity relaxation time of dust particles in response to the enhancement of β, which triggers the particles to accelerate until their motion and Casson fluid velocity become identical. Next, from Figures 4 and 5, it can be noticed that increasing effect of ϕ encourages the motion and heat distributions of all phases. These occurrences occurred because of nanoparticles become increasing factor in enhancing the heat transfer. Moreover, parameter ϕ produces a significant effect on fluid temperature as compared to velocity since a marked difference in the temperature distribution can be discovered when the value of ϕ is varied.

Table 3

Comparison of $C_f Re_x^{1/2}$ for different values of M and A when $\beta = 0$, $\alpha_1 = \pi/2$

M	A	Exact equation (18)	Nadeem *et al.,* [30]	Present
0	∞	1.0000	1.0042	1.0000
	5	1.0954	1.0954	1.0954
	1	1.4142	1.4142	1.4142
10	∞	-	3.3165	3.3166
	5	-	3.6331	3.6332
	1	-	4.6904	4.6904

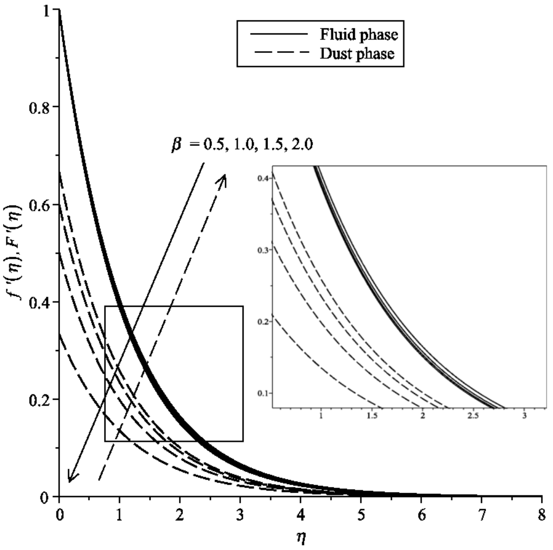

Fig. 2. Influence of β on velocity profile

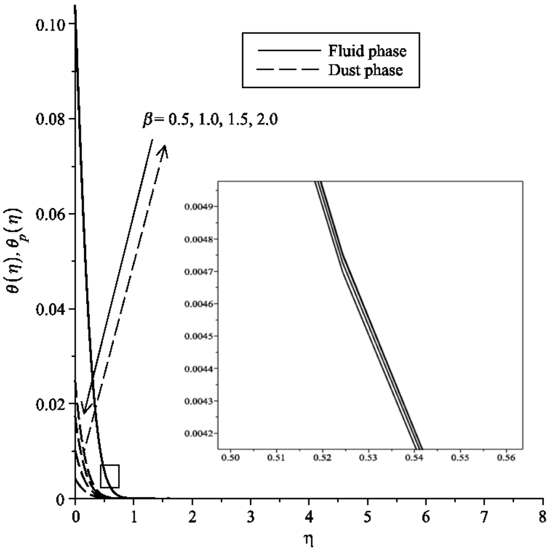

Fig. 3. Influence of β on temperature profile

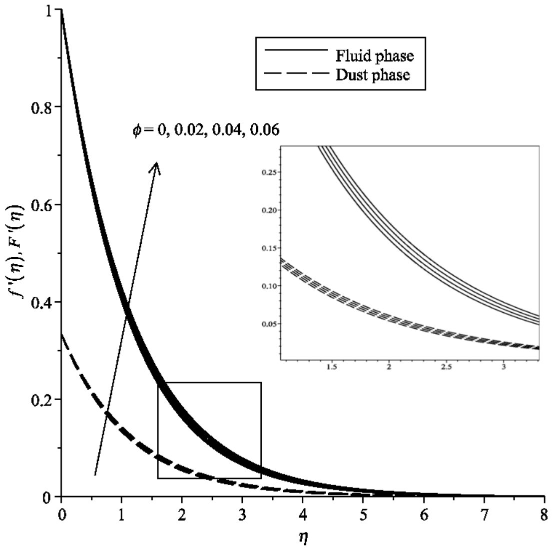

Fig. 4. Influence of ϕ on velocity profile

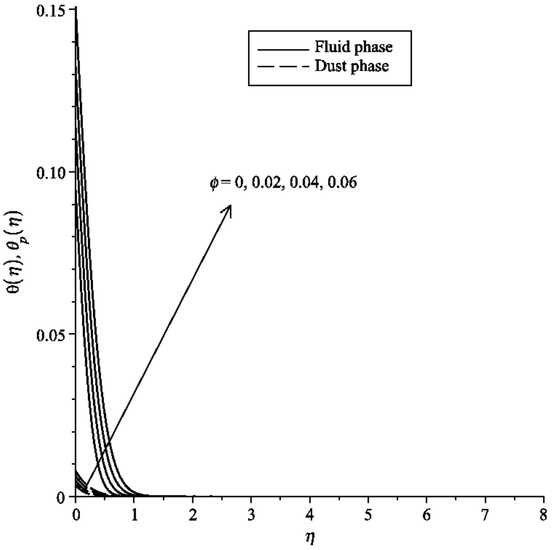

Fig. 5. Influence of ϕ on temperature profile

4. Conclusions

Numerical investigation on aligned magnetic field flow past a vertical stretching sheet under consideration of accumulation of dust particles and SWCNTs in Casson fluid with NH is performed. The mathematical equations describing the proposed problem is initially presented in this study, where the distributions of fluid and dust phases can then be determined. The findings of this study suggest that a similar trend in all displayed figures can be noticed in all phases. In addition, an insignificant change occurs in fluid phase with response to the influence of involved parameters except for temperature profile of ϕ. The findings from this study therefore contributes in the development of two-phase fluid flow problem containing CNTs.

Acknowledgement

The authors gratefully acknowledge the financial support received in the form of fundamental research grants (FRGS) fund from the Ministry of Higher Educational, Malaysia, FRGS/1/2021/STG06/UITM/02/2 and Universiti Teknologi MARA (600-UiTMCTKD (PJI/RMU 5/2/1) RCF-RACER 2021 (7/2021)).

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