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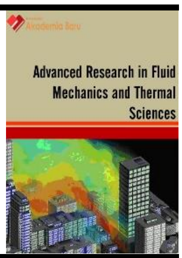

Fluid-Particle Interaction with Buoyancy Forces on the Jeffrey Fluid with Newtonian Heating

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ABSTRACT

The numerical results of fluid flow problem that being embedded with the dust particles is presented in this paper. In order to analyze such problem, a two-phase model is constructed by introducing a fluid-particle interaction forces in the momentum equations of fluid and dust phases. The buoyancy forces and aligned magnetic field are considered on the fluid flow. Also, the Newtonian heating boundary condition is induced on the vertical stretching sheet. The suitable similarity transformation is applied to the governing equations of the model which then produces the ordinary differential system. The results are obtained by adapting the Runge-Kutta Fehlberg (RKF45) method whereby the solutions are interpreted in terms of velocity and temperature profiles for Jeffrey fluid and dust particles respectively. The influences of assorted physical parameters are visualized graphically to clarify the flow and heat transfer characteristic for both phases. The discovery found that the presence of the dust particles have an effect on the fluid motion which led to decelerate the fluid transference. The present flow model can match to the single phase fluid cases if the fluid particle interaction parameter is ignored.

Keywords:
Two-phase flow, Dusty Jeffrey fluid, Aligned magnetic field, Newtonian heating

1. Introduction

Recent developments in the field of two-phase flow have led to a proliferation studies in the dynamics of solid particles through fluid. This solid-liquid system is governed in a separate continuum equations, by means the fluid and solid phases are individually formulated. The interaction force among two phases is significant, where usually, both governing equations are coupled through the term of total fluid-particle interaction force per unit volume that is clearly different from single phase flow. This phenomenon could be found in the flow of corpuscle in plasma, flow of liquid with suspended solids and etc. Altogether, it is a great helpful for modelling flow with binary mixture of non-Newtonian fluid and solid particles associated with particular circumstances. It can thus be

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suggested that this two-phase model could benefits in studying the dusty Jeffrey fluid that exhibits the binary characteristics of Jeffrey fluid and spherical dust particles such as undertaken here.

The Jeffrey fluid is selected for the study on account of its properties of relaxation and retardation times, simultaneously being recognised in polymer industries and biofluids [1]. Moreover, blood is a class of biofluids that has been proven experimentally showed the features of non-Newtonian fluids depending on the certain diseases state [2]. This corroborates the ideas of treating Jeffrey fluid model to study the blood flow specifically in a tapered artery containing a stenosis [3]. In addition, the stretching sheet acts as a driven force to initiate the movement of Jeffrey fluid, such works of [4-7]. They reached the conclusion that the fluid velocity has propensity to increase whereas fluid temperature did not show any significant decrease owing to the increasing Deborah number, which signify to the Jeffrey fluid parameter. Meanwhile, several studies thus far examined the Jeffrey fluid flows through the miscellaneous formation [8-11]. These rapid researches have consistently shown its suitability for any flow field with particular conditions and also proved the validity of the fluid model.

Investigating the magnetohydrodynamics (MHD) has been an object of research for its important practices in engineering industries and medical sciences. Precisely, this is fundamental in MHD generators, power generators, reducing of blood draining in surgeries, magnetic particles serve as a transportation agent for drugs and etc. The mechanism of MHD embodies a mutual relationship of electrically conduit fluid and magnetic field, latter induced a force. Therefore likely to affect the rate of fluid motion and intensity of magnetic fields themselves. One study examined the magnetic field flow for Micropolar fluid under the influence of mixed convection along an inclined plate [12]. Meanwhile, the in-depth analysis of the Jeffrey fluid is attempted for MHD flow which revealed that the increasing magnetic fields has potentially decreased the fluid velocity whilst increased the temperature profile [13] . Furthermore, combining different types of fluid in the flow field creates another class of fluid model, provided that these fluids need to be compatible with each other. Recently, a number of studies have proposed Jeffrey fluid and viscoelastic fluid being incorporated with micropolar fluid for the case of aligned magnetic field flow [14,15]. In line with this case, however, it has been suggested for the dusty Casson fluid as in two-phase flow model and the solutions are obtained numerically for both Casson fluid and solid particles [16].

Motivated by the previous literature, the dusty Jeffrey fluid is proposed according to the established two-phase model of [17], as being initially mentioned. This initiative has demonstrated, for the first time the mixed convection flow of the proposed model by taking into account the impact of aligned magnetic field under conditions of Newtonian heating. In addition, an aligned magnetic field is equated to the coupling of parameters aligned angle and magnetic field together with velocity function in the fluid momentum equation. The flow state of dusty Jeffrey fluid is delineated through velocity and temperature profiles for all-inclusive parameters. It is interesting to note that each profile has the distributions for fluid and dust phases. The Runge-Kutta Fehlberg (RKF45) method is employed to obtain the findings herein.

2. Mathematical Formulation

This paper gives an account of stretching sheet flow with uniform velocity $u_w(x) = ax$, the x-axis is placed vertically and axis being normal to it as illustrated in Figure 1. The incompressible Jeffrey fluid having dust particles are transmitted along y- axis by assuming the mixed convection and an acute angle α_1 with magnetic field on the flow regime. The sheet surface is heated by Newtonian heating for which the heat transfer process could be measured.

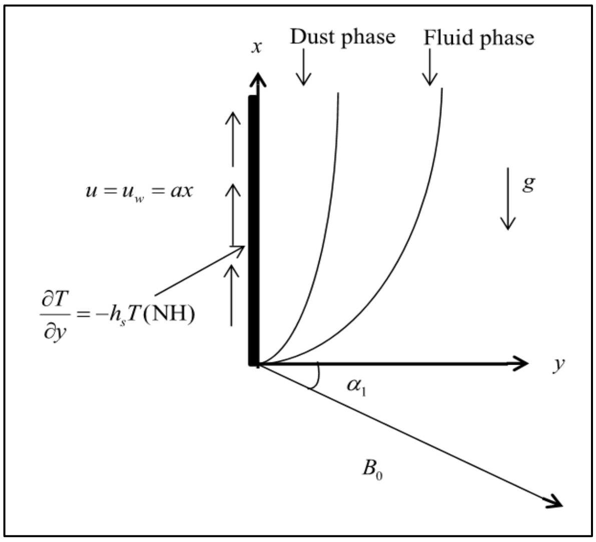

Fig. 1. Flow configuration

The constitutive expressions for the Jeffery fluid are

$$\mathbf{T} = -\rho \mathbf{I} + \mathbf{S}, \tag{1}$$

$$\mathbf{S} = \frac{\mu}{1+\lambda_2}\left(\dot{r} + \lambda_1 \ddot{r}\right), \tag{2}$$

where T, I, S are implies the Cauchy stress tensor, identity tensor and extra stress tensor, ρ is pressure, μ is dynamic viscosity, λ_1 and λ_2 are relaxation time and ratio of relaxation to retardation times respectively.

There are certain elements of the dilute dust particles which are deemed to have uniform size with spherical shape, non-interacting and number density is consistent all along the motion. In consideration of this and some published studies [17-19], the following are the present boundary layer governing equations for steady two dimensional fluid flow of dusty Jeffrey

Fluid phase

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{3}$$

$$\begin{aligned} u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\nu}{1+\lambda_2}\left[\frac{\partial^2 u}{\partial y^2} + \lambda_1\left(u\frac{\partial^3 u}{\partial x \partial y^2} + v\frac{\partial^3 u}{\partial y^3} - \frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2} + \frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x \partial y}\right)\right] + \frac{\rho_p}{\rho \tau_v}(u_p - u) \\ -\frac{\sigma u B_0^{\,2}}{\rho}\sin^2\alpha_1 + g\beta^*(T - T_\infty), \end{aligned} \tag{4}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{\rho_p c_s}{\gamma_T}(T_p - T), \tag{5}$$

Dust phase

$$\frac{\partial u_p}{\partial x}+\frac{\partial v_p}{\partial y}=0 \tag{6}$$

$$\rho_p\left(u_p\frac{\partial u_p}{\partial x}+v_p\frac{\partial u_p}{\partial y}\right)=\frac{\rho_p}{\tau_v}(u-u_p), \tag{7}$$

$$\rho_p c_s\left(u_p\frac{\partial T_p}{\partial x}+v_p\frac{\partial T_p}{\partial y}\right)=-\frac{\rho_p c_s}{\gamma_T}(T_p-T) \tag{8}$$

where (u,v) and $(u_p,v_{p)}$ are the velocities components of the fluid and particle phase along x andy axes, respectively. μ is the coefficient of viscosity of the fluid, ρ and ρ_p are the density of fluid and dust phase, $\alpha_1$is the aligned angle, $\tau_v = 1/k$ is the relaxation time of particles phase, k is the Stoke's resistance (drag force), c_p and c_s are specific heat of fluid and dust particle, T and T_P are the temperature of fluid and particle phases, γ_T is the thermal relaxation time, B_0 is the magnetic-field strength, g is the gravity acceleration, and β^* is the thermal expansion coefficient.

The governing equations stated above need to be transformed into convenient form along with these boundary conditions

$$u=u_w(x)=ax,\;\; v=0,\;\; \frac{\partial T}{\partial y}=-h_s T \quad \text{at } y=0$$

$$u\to 0,\;\; u_p\to 0,\;\; v_p\to v,\;\; T\to T_\infty,\;\; T_p\to T_\infty \quad \text{as } y\to\infty \tag{9}$$

where a is positive constant and h_s is heat transfer parameter.

To solve the problem formulation, Eqs. 3 -9 are required to employ the following similarity transformation. Additionally, $u = -\partial\Psi/\partial y$ and $v = -\partial\Psi/\partial x$ in which Ψ is defined as the stream function. Thereby, they can be expressed

$$u=axf'(\eta),\;\; v=-(av)^{1/2}f(\eta),\;\; \eta=\left(\frac{a}{v}\right)^{1/2}y,\;\; \theta(\eta)=\frac{T-T_\infty}{T_\infty}$$

$$u_p=axF'(\eta),\;\; v_p=-(av)^{1/2}F(\eta),\;\; \theta_p(\eta)=\frac{T_p-T_\infty}{T_\infty}, \tag{10}$$

Definitely, hence ensuing, that the ordinary differential equations of both phases are

$$f'''+(1+\lambda_2)\left(ff''-f'^2\right)+De\left(f''^2-ff^{(4)}\right)+(1+\lambda_2)\beta N\left(F'-f'\right)-(1+\lambda_2)M\sin^2\alpha_1 f'$$
$$+(1+\lambda_2)\lambda\theta=0, \tag{11}$$

$$\theta'' + \Pr f\theta' + \frac{2}{3}\beta N\left(\theta_p - \theta\right) = 0, \tag{12}$$

$$F'^2 - FF'' + \beta\left(F' - f'\right) = 0, \tag{13}$$

$$\theta_p{}' F + \frac{2}{3}\frac{\beta}{\Pr\gamma}\left(\theta - \theta_p\right) = 0 \tag{14}$$

and the boundary conditions (9) are now can be indicated in the form of

$$f(0) = 0,\ f'(0) = 1,\ \theta'(0) = -b\left(1 + \theta(0)\right) \quad \text{at } \eta = 0$$

$$f'(\eta) \to 0,\ f''(\eta) \to 0,\ F'(\eta) \to 0,\ F(\eta) \to f(\eta),\ \theta(\eta) \to 0,\ \theta_p(\eta) \to 0 \quad \text{as } \eta \to \infty \tag{15}$$

where a prime (‘) denotes differentiation with respect to η. De is Deborah number, N is the mass concentration of particle phase, M is the magnetic field parameter, β is the fluid-particle interaction parameter, Pr is the Prandtl number, γ is the specific heat ratio of mixture, b is the conjugate parameter for NH and λ is the buoyancy parameter with Gr_x is the Grashof number and Re_x is the Reynolds number. These parameters can be denoted as

$$De = \lambda_1 a, \quad N = \frac{\rho_p}{\rho}, \quad M = \frac{\sigma B_0^2}{\rho a}, \quad \beta = \frac{1}{a\tau_v}, \quad \Pr = \frac{\mu c_p}{k}, \quad \gamma = \frac{c_s}{c_p}, b = -h_s\left(\frac{v}{a}\right)^{1/2},$$

$$\lambda = \frac{Gr_x}{\text{Re}_x{}^2}, \quad Gr_x = \frac{g\beta^* T_\infty x^3}{v^2}, \quad \text{Re}_x = \frac{u_w(x)x}{v}.$$

Eq. 16 is devoted to the exact solution of 11 for Jeffrey fluid flow and can be expressly stated as [4]

$$f(\eta) = \frac{1 - \exp\left(-m\eta\right)}{m}, \quad m = -\left(\frac{1 + \lambda_2}{1 + De}\right)^{(1/2)} \tag{16}$$

The skin friction coefficient C_f and the local Nusselt number Nu_x are measured using the expressions of

$$C_f = \frac{\tau_w}{\rho U^2(x)}, \quad Nu_x = \frac{xq_w}{k(T_w - T_\infty)}, \tag{17}$$

in which

$$\tau_w = \frac{\mu}{1 + \lambda_2}\left[\frac{\partial u}{\partial y} + \lambda_1\left(u\frac{\partial^2 u}{\partial x \partial y} + v\frac{\partial^2 u}{\partial y^2}\right)\right]_{y=0}, \quad q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=0} \tag{18}$$

with $\mu = \rho v$. τ_w, q_w and k are clearly be defined as the rate of heat transfer, surface heat flux and thermal conductivity. Introducing (10) and using (18) into (17), the following expressions are then ensued as

$$C_f \mathrm{Re}_x^{1/2} = \left(\frac{1+De}{1+\lambda_2}\right) f''(0), \qquad Nu_x \mathrm{Re}_x^{-1/2} = \gamma\left(1+\frac{1}{\theta(0)}\right). \tag{19}$$

Here, $Re_x = (ax^2/v)$ is the Reynolds number.

3. Methodology

The present model constituted of governing equations and appropriate boundary conditions for Jeffrey fluid and dust particle respectively. Prior to undertaking the numerical solutions, they are transformed to the ordinary differential equations (11)-(15). The numerical method of Runge-Kutta Fehlberg (RKF45) is one of the more practical approaches to adopt for this problem in which the computation is set up in the Maple software. The profiles of velocity and temperature for all phases are plotted with a view to analyses the behavior of dusty Jeffrey fluid responded to the physical parameters. The selection of finite boundary layer thickness η_∞ is prominent as it will determine the asymptotic behavior of the profile. For this reason, $\eta_\infty = 8$ is observed in all figures which also fulfill the boundary conditions of both phases and accordingly guarantees the accuracy of the obtained solutions.

4. Results and Discussion

This paper gives an account of stretching sheet The table and figures in this section represents the analyses of current solutions of dusty Jeffrey fluid, hereby the elaborations on the flow variation for each phase are provided. It is worth to mention that, this flow problem coincides with the published study of [19] under conditions of ignoring the parameters of $\alpha_1, M, \lambda, \beta, N$ and $\gamma \to \infty$. He used the numerical method of Keller-box for solving the Jeffrey fluid flow. Therefore, the values of skin friction coefficient $f"(0)$ between his research and recent finding are compared. In addition to that, the second derivative on the surface of exact Eq. 16 is also calculated to increase the reliability of solutions obtained herein. From Table 1, it can be seen that the values are in great concurrent. Apart from keeping these parameters as $Pr = 10, \alpha_1 = \pi/6, M = \lambda = 1, \beta = N = 0.5, \lambda_2 = De = 0.2, \gamma = 0.1, b = 0.3$ for the computation, the values are also varied consistently as illustrated in those respective figures and table.

Table 1
Comparative values of $f"(0)$ when $\lambda_2 = 0.2$ for the assorted value De

De	Exact equation	[19]	Present
0	-1.09544512	-1.09641580	-1.09544592
0.2	-1.00000000	-1.00124052	-1.00000000
0.4	-0.92582010	-1.00124052	-0.92582010
0.6	-0.86602540	-0.86755715	-0.86602541
0.8	-0.81649658	-0.81808091	-0.81649659
1.0	-0.77459667	-0.77618697	-0.77459668

Figures 2 and 3 show the impact of fluid particle interaction parameter β for dusty Jeffrey fluid. The similar trends have been depicted in the figures for the rising values of β for both profiles and phases. The increasing of β led to the reduction of the relaxation time of dust particle τ as they are being inversely proportional. Following this, the dust particles are moving fast in that way of adapting to the fluid motion, accordingly, the particles generate the drag force when encounter with fluid. Based on this fact, the observed increase (decrease) in dust (fluid) velocity and temperature profiles are exposed in those figures.

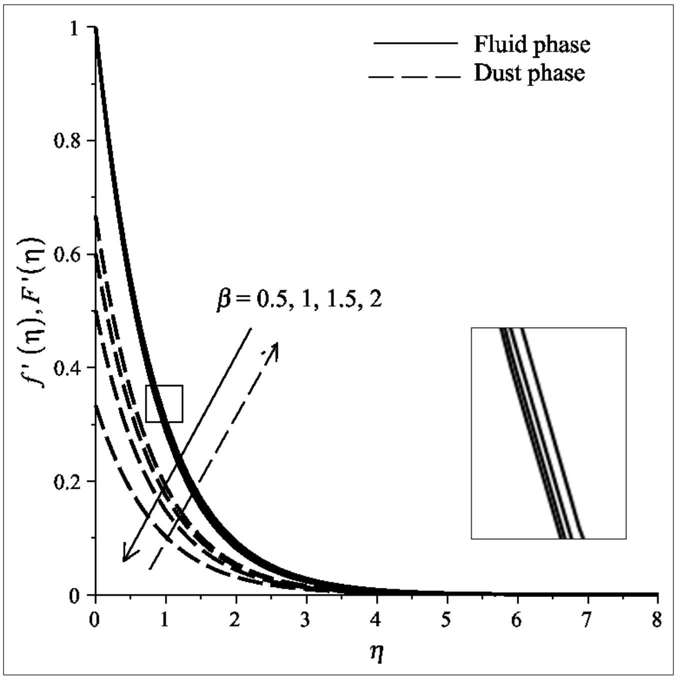

Fig. 2. Variation of β on the velocity profile

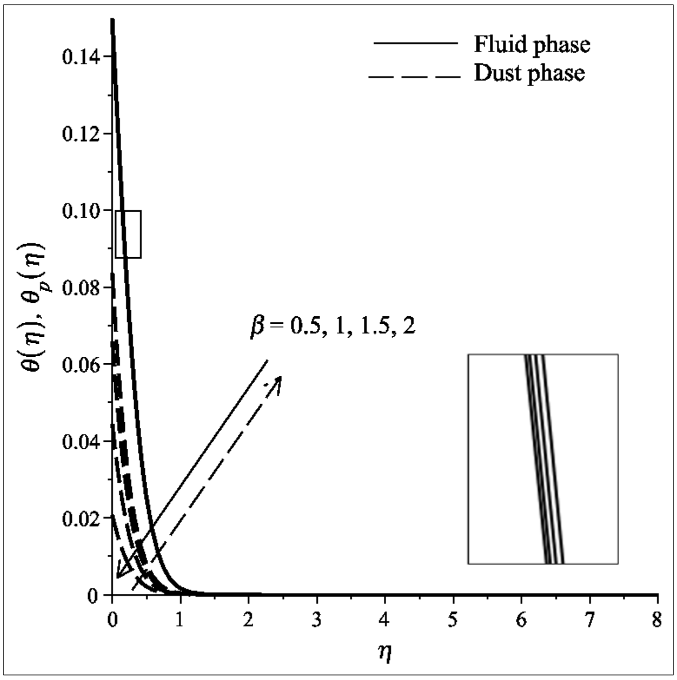

Fig. 3. Variation of β on the temperature profile

Figures 4 -7 present the influences of magnetic field parameter M and aligned angle α_1 on the flow field and heat transfer process, respectively. Seeing that parameters M and α_1 in fifth term of Eq. 11, they are appears to be correlated. The increasing α_1 strengthens the intensity of magnetic field and physically encouraged the drag forces (Lorentz force) that actuate opposite to the flow direction, ultimately decreased the velocities in both phases. It also has effect on the increment of temperature profile for fluid and dust phases. The present findings is appertain to the classical problem of mixed convection flow for transverse magnetic field effect on condition that $\alpha_1 = \pi/2$, while, when $\alpha_1 = 0$ the effect is completely ignored. It is interesting to scrutinize this effect to other angle other than being transverse or perpendicular to the flow direction.

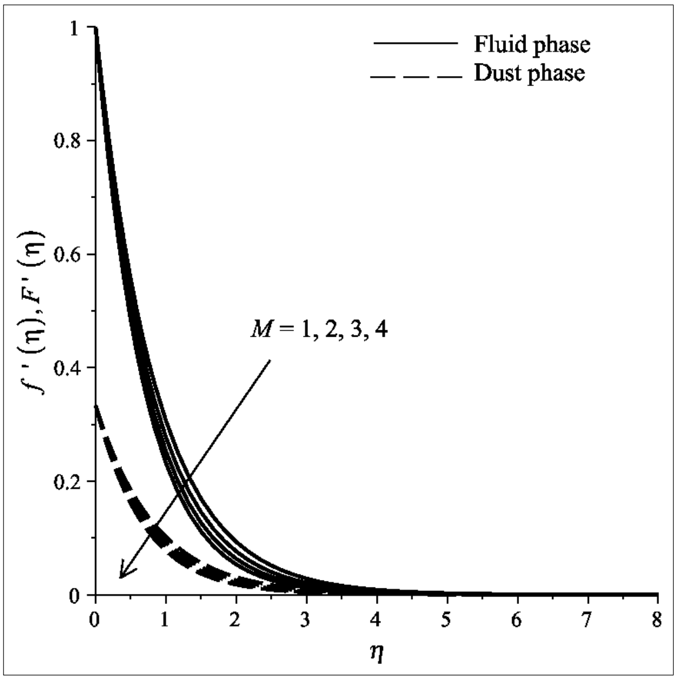

Fig. 4. Variation of M on the velocity profile

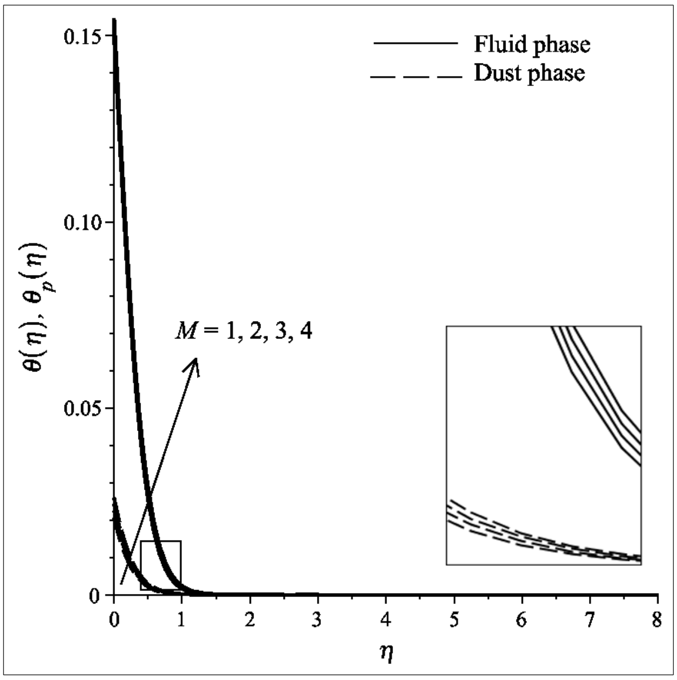

Fig. 5. Variation of M on the temperature profile

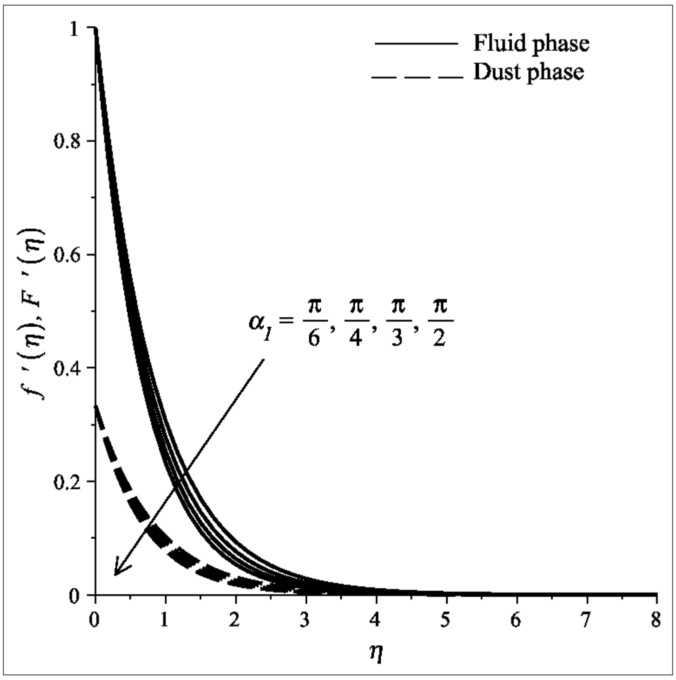

Fig. 6. Variation of α_1 on the velocity profile

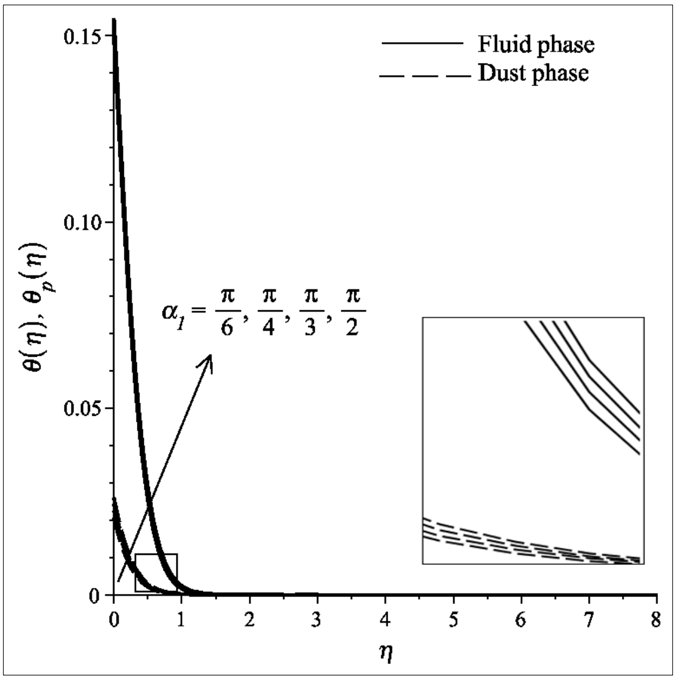

Fig. 7. Variation of α_1 on the temperature profile

Figures 8 and 9 demonstrate the outcomes of introducing Deborah number De to the flow region. The fluid velocity is detected to rise along with the heightening value in De whilst the dust motion seems to abate. Meanwhile, the temperature profile for all phases is decreasing with an increase in De. Noted that, in a mathematical description of $e = \lambda_1$a, both De and the product of λ_1 and a are typified to proportional.

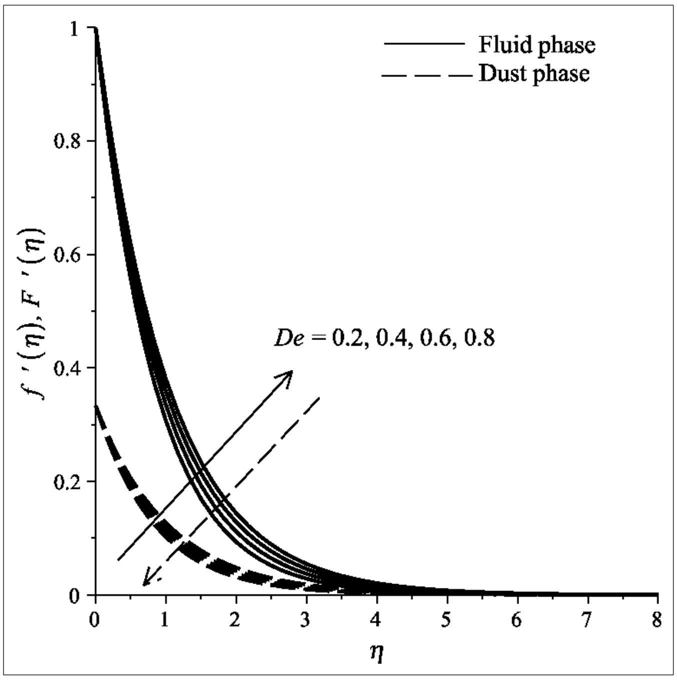

Fig. 8. Variation of De on the velocity profile

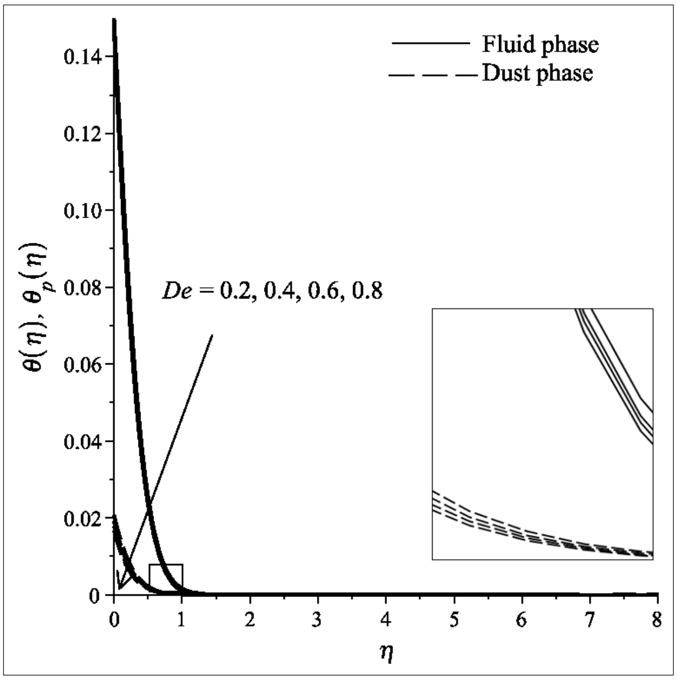

Fig. 9. Variation of De on the temperature profile

Figures 10 and 11 on the other hand display the assorted value of λ_2 for both phases. It is perceived that, the augmented value in λ_2 gives rises to the relaxation time which decelerates the fluid velocity. In contrast, the dust velocity and the temperature profile of two phases are seen to enhance.

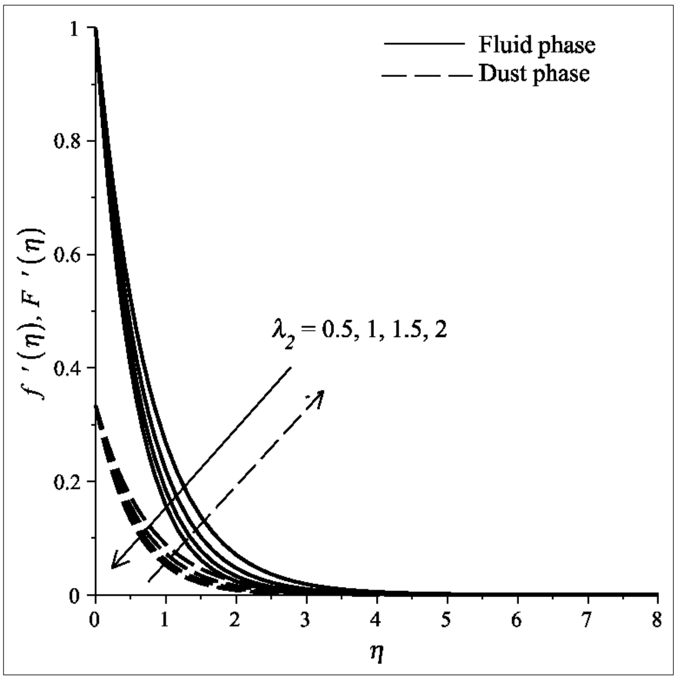

Fig. 10. Variation of λ_2 on the velocity profile

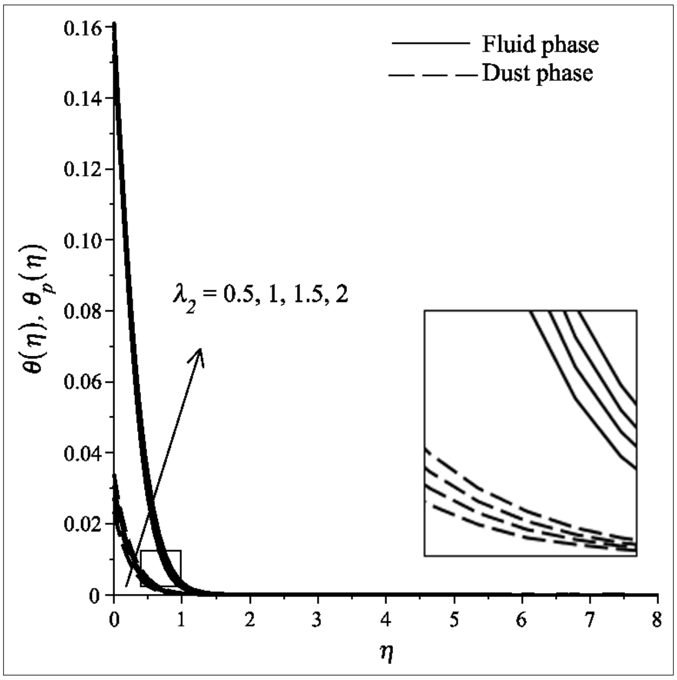

Fig. 11. Variation of λ_2 on the temperature profile

Figures 12 and 13 show that there has been a slight change in both profiles corresponds to the various value of mixed convection parameter λ. It is likely owing to a high Prandtl number of fluid having large density, as its less susceptible to λ (i.e. $Pr = 10$ is computed throughout the study). This is also accords with previous observations carried out by [20], which showed a marked alteration in the velocity and temperature profiles when $Pr = 1$. The increasing λ effectuates the developing of buoyancy force over a flow regime which performs as a favourable pressure gradient that facilitates the fluid transport and enhances the surface heat transfer. Therefore, the velocity and temperature profiles are observe to increase and decrease, respectively as appeared in those figures for both phases.

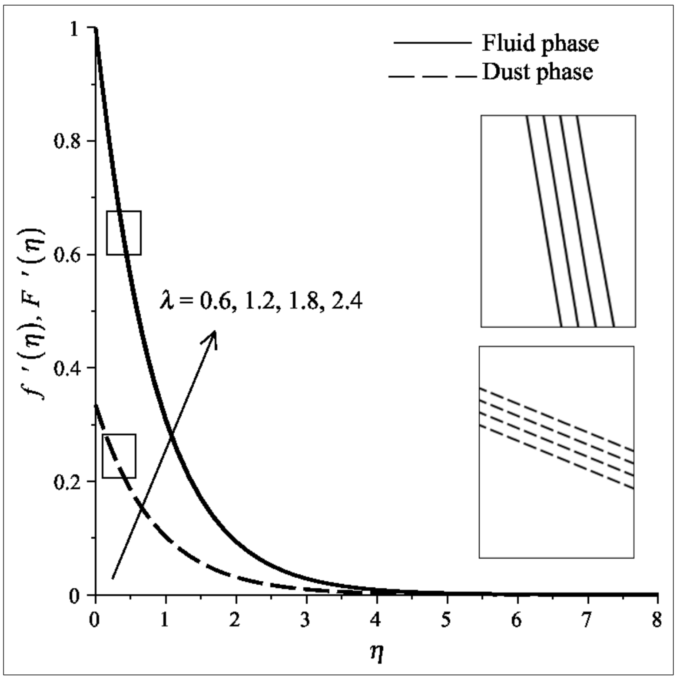

Fig. 12. Variation of λ on the velocity profile

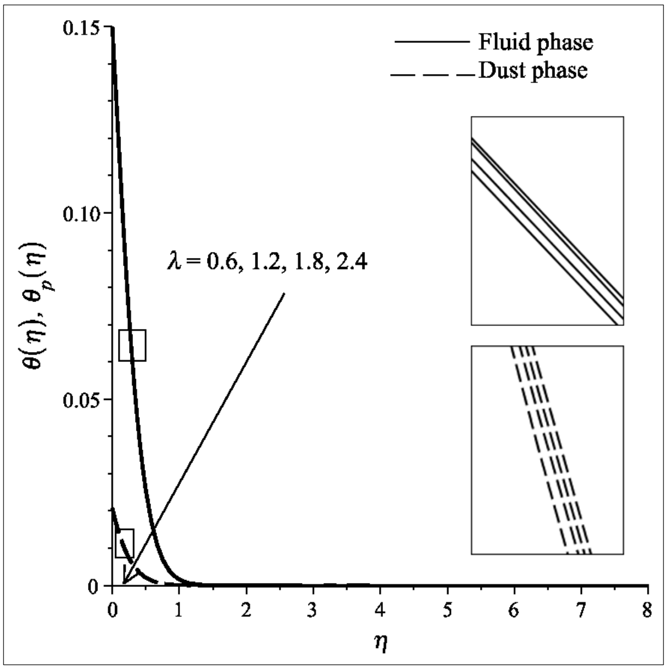

Fig. 13. Variation of λ on the temperature profile

Figures 14 - 17 exhibit the Prandtl number Pr and conjugate parameter b are measured on dusty Jeffery fluid. A decreasing trend in both profiles can be seen in Figures 14 and 15 corresponding to the enhancement value in Pr. It is commonly been clarified that a higher Pr value motivates the momentum diffusivity which also embodies to the increasing in fluid viscosity and unambiguously hinder fluid migration. Ensuingly, the temperature profile for all phases is significantly deteriorated and lowers the thermal boundary layer thickness. For $Pr = 10$, the thermal boundary layer thickness approaching zero much faster compared to others value of Pr that has been exposed in Figure 15. This result accordance in all aforementioned temperature profiles which promptly attained the asymptotic behaviour. Oppositely, the increased b enhances both profiles for all phases. The changes for this can be explained by the fact that the heat transfer parameter h_s is increase at the surface and dusty Jeffrey fluid is indeed absorb more heat from the surface that encourages a rise in temperature profile.

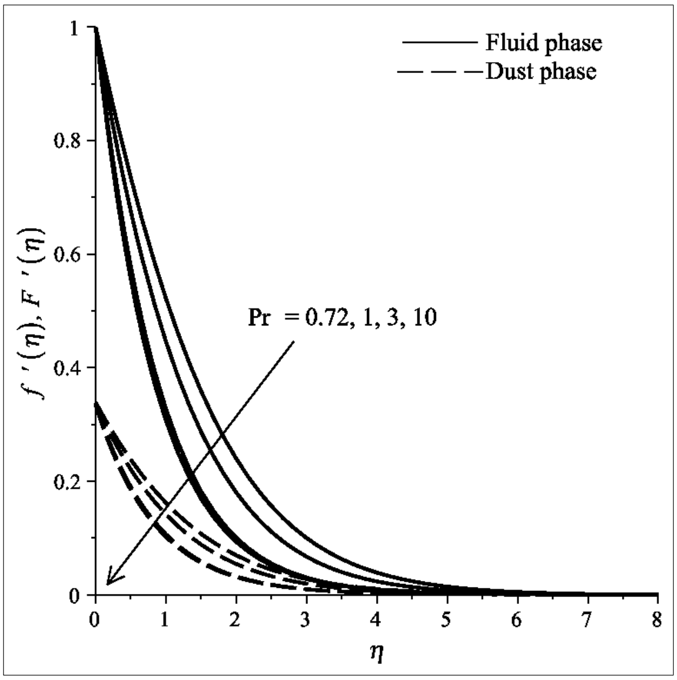

Fig. 14. Variation of Pr on the velocity profile

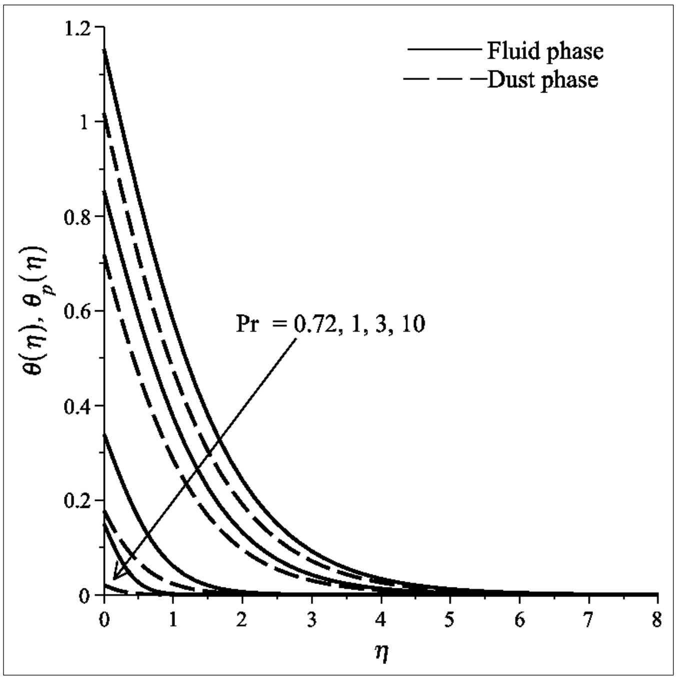

Fig. 15. Variation of Pr on the temperature profile

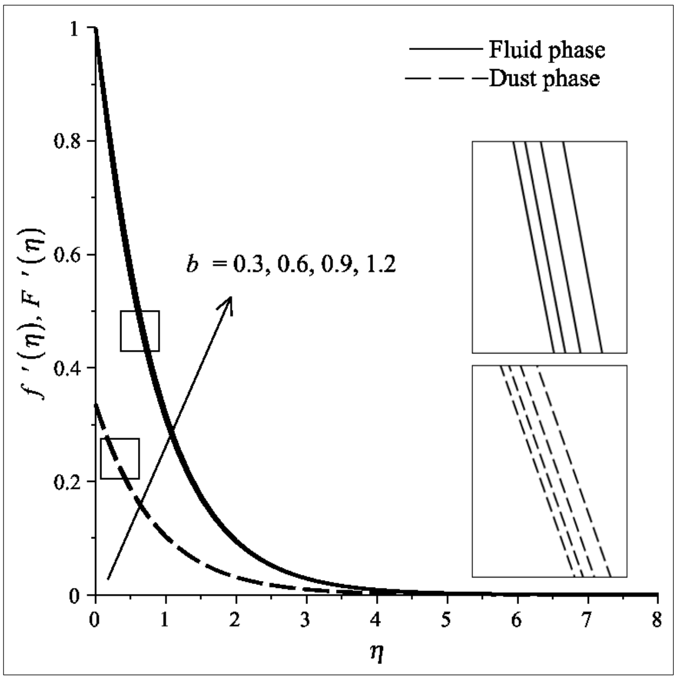

Fig. 16. Variation of b on the velocity profile

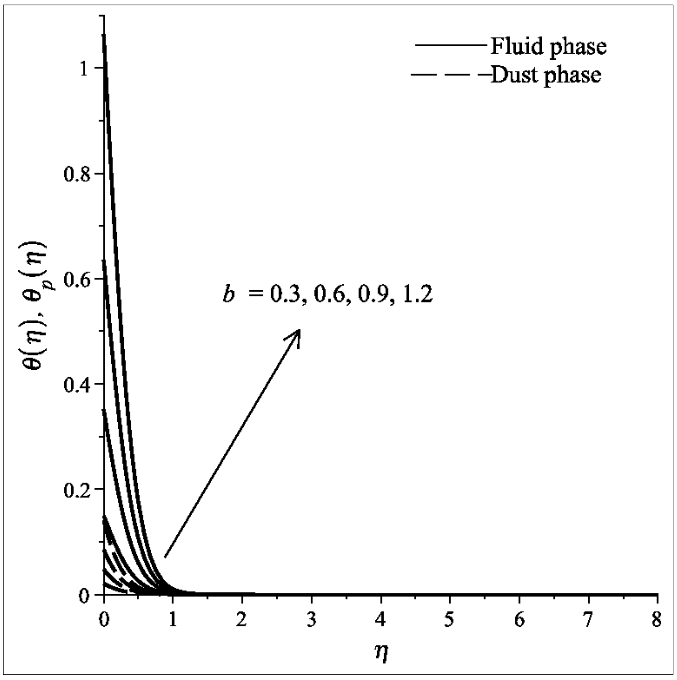

Fig. 17. Variation of b on the temperature profile

5. Conclusions

In this study, the Jeffrey fluid acts as a carrier to the dust particles whereby both of them move along the vertical stretching sheet. To enable the problem solving, some assumptions for all phases are considered reasonably. Taken together, a dusty Jeffrey fluid model is developed to determine the interaction between fluid-solid phases on the flow regime. Other than that, factors found to be influencing the present model are explored in which the numerical method is employed for this investigation. The results of this study indicate that the fluid velocity and temperature distributions are always higher than dust particles, besides, the opposite trend between both phases is noticed with β. Meanwhile, both phases share the similar trend in conjunction to the rest factors. Almost all of the temperature profiles are not showing a significant change since the viscosity of fluid is high which can be perceived in the figures. Furthermore, the present study extends some theoretical knowledge of two-phase flow.

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