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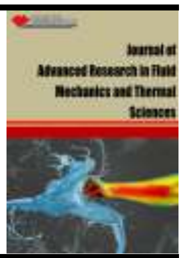

Forced Convection of MHD Radiative Jeffrey Nanofluid Over a Moving Plate

Syazwani Mohd Zokri[1,*], Nur Syamilah Arifin[2], Abdul Rahman Mohd Kasim[3,♣], Norhaslinda Zullpakkal[1], Mohd Zuki Salleh[3]

[1] Fakulti Sains Komputer & Matematik, Universiti Teknologi MARA Cawangan Terengganu, Kampus Kuala Terengganu, 21080 Terengganu, Malaysia
[2] Fakulti Sains Komputer & Matematik, Universiti Teknologi MARA Cawangan Johor, Kampus Pasir Gudang, 81750 Masai, Johor, Malaysia
[3] Pusat Sains Matematik, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia

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ABSTRACT

Convectively heated Jeffrey nanofluid flow in the presence of magnetic field and thermal radiation is investigated from a moving plate. Parameter of Brownian motion from Buongiorno model is the imperative mechanism that contributes to the heat transfer enhancement. Governing equations, consisting of the continuity, momentum, energy and nanoparticle concentrations equations are transformed into dimensionless form by means of the appropriate similarity transformation variables. Numerical results via Runge-Kutta Fehlberg Fourth-Fifth order (RKF45) method are specifically acquired on the impact of physical parameters such as Brownian motion, magnetic parameter, ratio of relaxation to retardation and radiation parameters over the temperature and nanoparticles concentration profiles. Comparison of the present results with existing published studies has validated the accuracy of the numerical solutions. Graphical representation of different magnetic parameters has caused the increment in both temperature and nanoparticles concentration profiles. On the other hand, enhancement of Brownian motion has intensified the temperature but declined the nanoparticles concentration.

1. Introduction

Much practical importance may be found through the exploration of boundary layer flow from a moving plate, to be exact in the paper production, aerodynamic extrusion of plastic sheets, cooling of an infinite metallic plate in a cooling bath and boundary layer along material handling conveyor. Nandeppanavar [1] explored the condition of melting heat transfer of a Casson fluid from a moving plate. Investigation was then continued by Maleki *et al.,* [2] on pseudo-plastic nanofluid flow with heat absorption/generation and viscous dissipation. Combined free and forced convection flow of

* *Corresponding author.*
E-mail address: syazwanimz@uitm.edu.my
♣ *Corresponding author.*
E-mail address: rahmanmohd@ump.edu.my

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nanofluid adjacent to a moving plate was reported by Jedi [3] with dual effect of partial slip and convectively heated thermal condition. Suction/injection was concentrated by Baharifard *et al.,* [4] on MHD micropolar fluid across a moving plate. A recent study by Kumar *et al.,* [5] tackled the Soret number and free convection effect on MHD Jeffrey fluid induced by a moving porous plate.

Nanofluids can be considered as one of the innovatory aspects in engineering and industrial applications including transportation, air-conditioning, ventilation, power generation, heating, cooling etc. Suspension of solid nanoparticles like water, oil, and ethylene glycol in the conventional fluids can increase the heat transfer performance. Shape and size are the thermal properties of the solid nanoparticles that highly affect the thermal conductivity of fluid [6-8]. An experiment conducted by Choi and Eastman [9] has proved that the incorporation of nanoparticles in the non-Newtonian fluids had greatly boosted the fluid thermal capability. To date, many have considered the inclusion of nanoparticles in non-Newtonian fluids, for instance Shah *et al.,* [10] in casson fluid, Waqas *et al.,* [11] in viscoelastic fluid, Zokri *et al.,* [12] in Jeffrey fluid, Zulkifli *et al.,* [13] in micropolar fluid and Tlili *et al.,* [14] in Maxwell fluid. Their studies have highlighted that the random movement of nanoparticles, namely the Brownian motion parameter, helps in enhancing the thermal conductivity.

Of all the non-Newtonian fluids, Jeffrey fluid is one of such materials that portray the imperative characteristic of retardation and relaxation times. Efforts on Jeffrey nanofluid flow have been done over numerous flow features considering such fascinating rheological behaviour. Ramzan *et al.,* [15] examined the combined impacts of thermal and concentration stratification, thermal radiation and heat generation/absorption on Jeffrey fluid flow across an inclined stretched cylinder with suspended nanoparticles. Exploration of magnetohydrodynamic, Joule heating and radiation was carried out by Ramzan *et al.,* [16] in Jeffrey nanofluid flow induced by a linearly stretched surface. Gireesha *et al.,* [17] reported the heat generation/absorption and nonlinear thermal radiation on Jeffrey nanofluid from a nonlinear permeable stretched sheet. Zokri *et al.,* [18] incorporated the Buongiorno model to investigate the Jeffrey fluid flow over a horizontal circular cylinder with assimilation of nanoparticles and viscous dissipation effect. Very recently, flow of Jeffrey fluid with suspended nanoparticles was studied by Naidu *et al.,* [19] to inspect the amalgamated impacts of thermal radiation and partial slip from a vertical stretching sheet.

In all of the above-cited works, it is clear that there was no research found that combined the impacts of MHD, thermal radiation and suspended nanoparticles under convective boundary conditions. Pertaining to the substantial influence of these impacts over the convective boundary conditions, the present study aims to investigate the MHD Jeffery nanofluid flow from a moving plate with thermal radiation under convective boundary condition.

2. Problem Formulation

Suppose a steady two-dimensional flow of Jeffrey fluid passing through a moving plate with constant velocity $u_w(x)$ is taken into consideration, as displayed in Figure 1. The combined impact of thermal radiation and passive control of nanoparticles is incorporated. A perpendicular direction of magnetic field, B_0 is oriented to the plate. In addition, the boundary layer temperature, ambient temperature, hot fluid temperature, nanoparticle concentration and ambient nanoparticle concentration are represented as T, T_f, T_∞, C and C_∞. Under these physical conditions, the governing partial differential equations can be written as the following [20, 21],

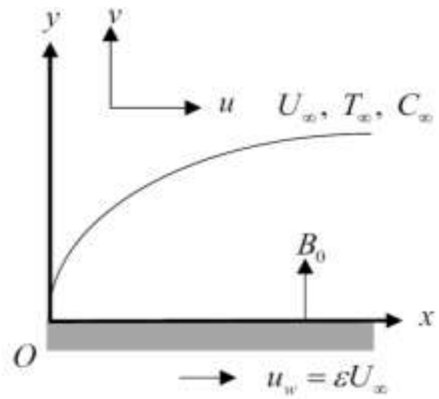

Fig. 1. The flow diagram

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\nu}{1+\lambda}\left[\frac{\partial^2 u}{\partial y^2}+\lambda_1\left(u\frac{\partial^3 u}{\partial x\partial y^2}+\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial x\partial y}-\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial y^2}+v\frac{\partial^3 u}{\partial y^3}\right)\right]-\frac{\sigma B_0^2}{\rho_f}u \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]-\frac{1}{(\rho c_p)_f}\frac{\partial q_r}{\partial y} \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}+D_B\frac{\partial^2 C}{\partial y^2} \tag{4}$$

with boundary conditions

$$\begin{aligned}&u=u_w(x)=\varepsilon U_\infty,\ v=V_w,\ -k_f\frac{\partial T}{\partial y}=h_1(T_f-T),\ -D_B\frac{\partial C}{\partial y}=h_2(C_f-C)\ \text{ at }\ y=0\\&u\to U_\infty,\ v\to 0,\ T\to T_\infty,\ C\to C_\infty\ \text{ as }\ y\to\infty\end{aligned} \tag{5}$$

Imposing and applying the Rosseland approximation $q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y}$, Eq. (3) becomes [22],

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\left(\frac{k}{\rho C_p}+\frac{16\sigma^* T_\infty^3}{3k^*\rho C_p}\right)\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{6}$$

Let $Nr=\frac{4\sigma^* T_\infty^3}{k^* k}$ be the radiation parameter. Eq. (6) becomes

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\left(1+\frac{4Nr}{3}\right)\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{7}$$

where u and v are the respective components of velocity in the $x-$ and $y-$directions, σ^* is the Stefan-Boltzmann constant, k^* is the mean absorption coefficient, $V_w(x)$ is the velocity of suction/injection, ε is the plate velocity parameter, ρ_p is the particle density, ν is the kinematic viscosity, U_∞ is the free stream velocity, λ and λ_1 are the respective ratio of relaxation to retardation times and retardation time, σ is the electrically conductivity, ρ_f is the density for the base fluid, q_r is the radiative heat flux, D_B is the Brownian diffusion coefficient, h_f is the coefficient of heat transfer, $\alpha = \frac{k_f}{(\rho c_p)_f}$ is the thermal diffusivity, $\tau = \frac{(\rho c_p)_p}{(\rho c_p)_f}$ is the ratio of heat capacity where $(\rho c_p)_p$ is the heat capacity of the nanoparticle while $(\rho c_p)_f$ is the heat capacity of the fluid, k_f is the thermal conductivity and D_T is the thermophoretic diffusion coefficients. Eq. (1) is satisfied when the stream function, ψ be defined as $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$ and Eq. (2) to (5) become,

$$f''' - \frac{\lambda_2}{2} f f^{(iv)} + (1+\lambda)(f f'' - 2Mf') = 0 \quad (8)$$

$$\frac{1}{Pr}\left(1 + \frac{4Nr}{3}\right)\theta'' + f\theta' + Nb\theta'\phi' + Nt\theta'^2 \quad (9)$$

$$\phi'' + Le\, Pr\, f\, \phi' + \frac{Nt}{Nb}\theta'' = 0 \quad (10)$$

$$f(0) = f_w, f'(0) = \varepsilon, \theta'(0) = -Bi_1(1-\theta(0)),\ \ \phi'(0) = -Bi_2(1-\phi(0)),$$
$$f'(\infty) \to 1,\ \ f''(\infty) \to 0,\ \ \theta(\infty) \to 0,\ \ \phi(\infty) \to 0 \quad (11)$$

provided the implementation of the following similarity transformation variables [23],

$$\psi = (2U_\infty x v)^{1/2} f(\eta),\ \ \eta = \left(\frac{U_\infty}{2xv}\right)^{1/2} y,\ \ \theta(\eta) = \frac{T - T_\infty}{T_f - T},\ \ \phi(\eta) = \frac{C - C_\infty}{C_f - C} \quad (12)$$

where the mass suction/injection is denoted as $f_w = \frac{-V_w}{\sqrt{\frac{av}{2}}}$, for which $f_w < 0$ is the mass injection while $f_w > 0$ is the mass suction. Free convection flow, the downstream and upstream movement of the plate from the origin happen when $\varepsilon = 0$, $\varepsilon > 0$ and $\varepsilon < 0$, respectively [24]. η is the similarity variable, θ is the dimensionless temperature of the fluid and ϕ is the rescaled nanoparticle concentration. Furthermore, the parameters arise in Eq. (8) to (11) are denoted as follows

$\lambda_2 = \frac{\lambda_1 U_\infty}{x}$ (Deborah number), $M = \frac{\sigma x B_0^2}{U_\infty \rho_f}$ (magnetic parameter), $Pr = \frac{v}{\alpha}$ (Prandtl number), $Nb = \frac{\tau D_B C_\infty}{v}$ (Brownian motion), $Nt = \frac{\tau D_T (T_f - T_\infty)}{v T_\infty}$ (thermophoresis diffusion parameter), $Le = \frac{\alpha}{D_B}$ (Lewis number), and $Bi_1 = -\frac{h_1}{k}\left(\frac{v}{a}\right)^{1/2}$ and $Bi_2 = -\frac{h_2}{k}\left(\frac{v}{a}\right)^{1/2}$ (Biot number).

3. Results and Discussion

Numerical approach via Runge-Kutta Fehlberg method encoded in Maple software is tackled to solve the initial and boundary value problems given in Eq. (8)-(12). The entire investigation is directed to the aftermaths of flow field, temperature, and nanoparticle concentration profiles. Analysis of the results is carried out on four different parameters such as the magnetic field M, thermal radiation Nr, ratio of relaxation to retardation times λ and Brownian motion Nb. The default parameters used in this study are $\lambda = 0.1, M = 0.7, \lambda_2 = 0.2, Nb = 0.1, Pr = 7, Nt = 0.5, Le = 0.5, Bi_1 = Bi_2 = 0.2,\ \varepsilon = 0.1, f_w = 0.3, \gamma = 0.5$ and $Nr = 1.0$, unless stated elsewhere. Table 1 shows the comparison values of $-\frac{\theta'(0)}{\sqrt{2}}$ for different values of Prandtl number Pr when $Bi_1 \to \infty, \varepsilon = \lambda = Bi_2 = \lambda_2 = Nt = Nb = Le = Nr = M = f_w = 0$. This comparison has clearly certified the authenticity of the numerical results where the present results generated with the help of Maple are in a good agreement with those of Mohamed *et al.,* [21], Bataller [22], Roşca and Pop [25] and Zokri *et al.,* [12].

Table 1
Numerical values of $-\frac{\theta'(0)}{\sqrt{2}}$ for various values of Pr when $Bi_1 \to \infty$ $\varepsilon = \lambda = \lambda_2 = Bi_2 = Nb = Nt = Le = M = Nr = f_w = 0$

Pr	Bataller [22]	Roşca and Pop [25]	Mohamed *et al.,* [21]	Zokri *et al.,* [12]	Present
0.7	0.29268	0.29268	0.292680	0.292778	0.292865
0.8	-	0.30691	0.306917	0.307005	0.307104
1	-	0.33205	0.332057	0.332140	0.332236
5	0.57669	0.57668	0.576689	0.576683	0.576683
10	0.72814	0.72814	0.728141	0.728140	0.728140

Figure 2 and 3 are plotted to examine the outcome of magnetic parameter, M on the profiles of temperature and concentration. These profiles are found to augment as M increases. This outcome is expected as the polarisation of fluid occurs due to electrically conducting fluid tends to modify the temperature profile. The Lorentz force comes to be stronger as a result of magnetic effect, thus thickening both the thermal and concentration boundary layer.

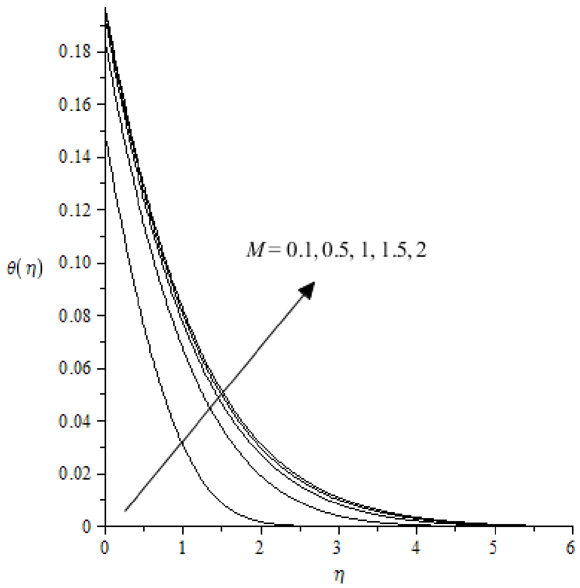

Fig. 2. Variation of temperature $\theta(\eta)$ versus M

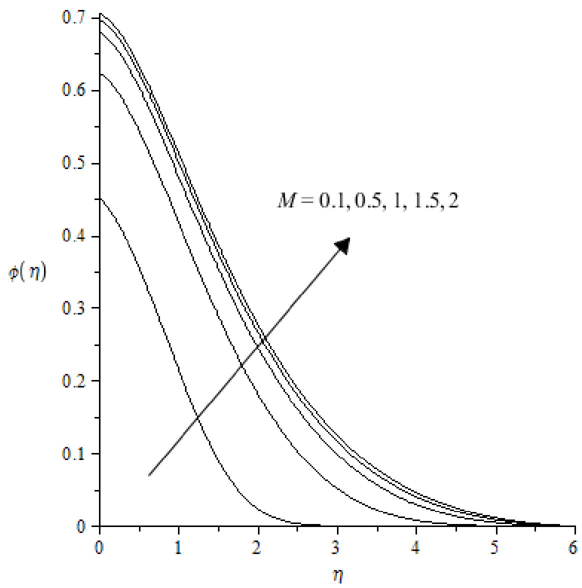

Fig. 3. Variation of nanoparticle concentration $\phi(\eta)$ versus M

Figure 4 discusses about effect of radiation parameter, Nr over temperature profile. An increasing impact of temperature profile owing to increased Nrvalues are observed because of the additional heat that is supplied to the surface. This circumstance has incraesed the thermal boundary layer flow. Plots of the temperature profile for ratio of relaxation time to retardation time, λ is revealed in Figure 5. It is found that the temperature of fluid and its associated thermal boundary layer thickness are enlarged due to rising value of λ.

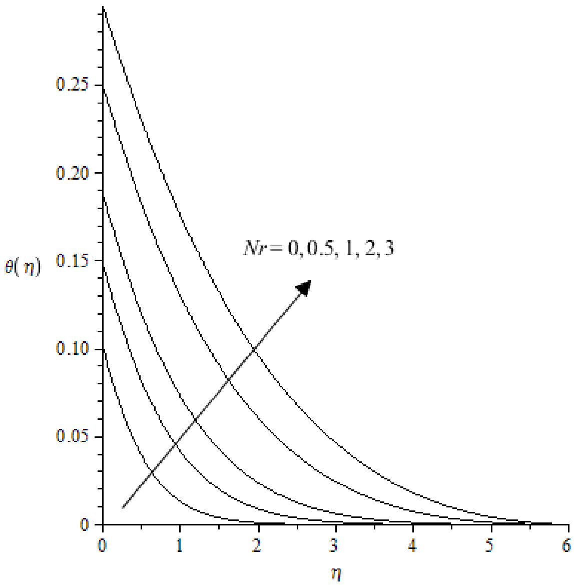

Fig. 4. Variation of temperature $\theta(\eta)$ versus Nr

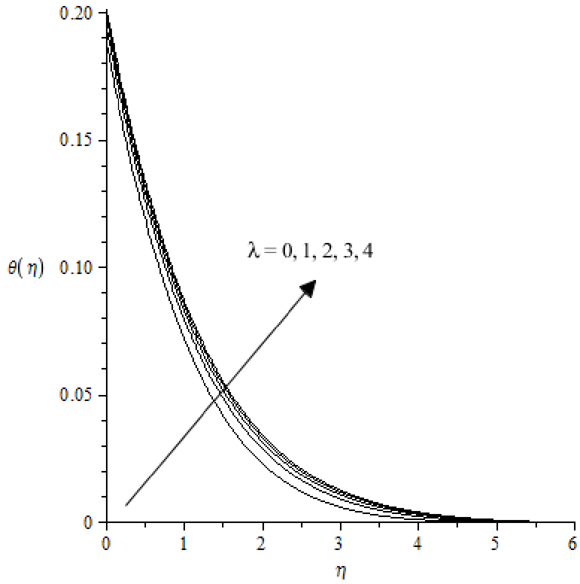

Fig. 5. Variation of temperature $\theta(\eta)$ versus λ

Figure 6 and 7 showcase how the Brownian motion, Nb parameter affects the profiles of temperature and nanoparticle concentration. Apparently, increased Nb values have increased the thickness of thermal boundary layer and decreased the thickness of concentration boundary layer. Here, incremented Nb values imply the enhanced arbitrary movement of nanoparticles that is initiated by the collision of molecules in the fluid. This random movement has led to the production of extra heat, hence the rising of temperature and the declining of nanoparticle concentration are foreseen.

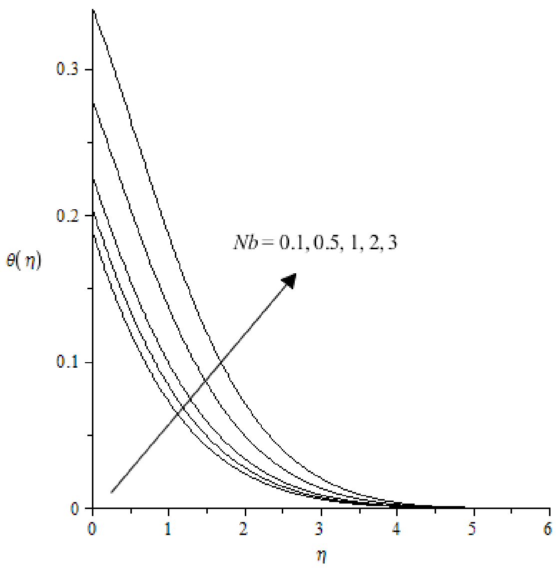

Fig. 6. Variation of temperature $\theta(\eta)$ versus Nb

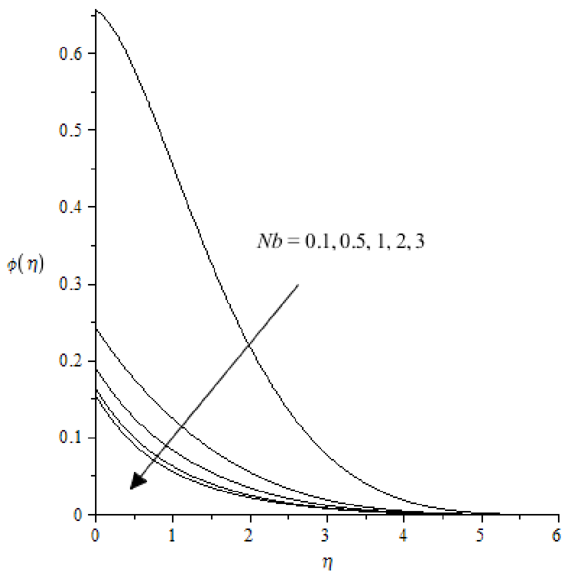

Fig. 7. Variation of nanoparticle concentration $\phi(\eta)$ versus Nb

4. Conclusion

The Jeffrey nanofluid flow passing through a moving plate with the thermal radiation impact is discoursed. Succeeding conclusions are the important outcomes of this investigation

i. Temperature and nanoparticle concentration profiles are enhanced with the rising M.
ii. Temperature profile is enhanced by virtue of parameters Nr and λ.
iii. Temperature profile is augmented and nanoparticle concentration is deteriorated owing to incremented Nt

Present study is limited to the active control of nanoparticles at the boundary. However, an assumption made by Nield and Kuznetsov [26] have revealed that one could control the value of the nanoparticle fraction at the boundary the same way one could control the temperature. Hence, this investigation is suggested to extend to a more physically acceptable model of passively controlled wall nanoparticle concentration. It is assumed that no normal mass flux at the plate and the particle fraction value adjusts accordingly.

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