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Alexandria Engineering Journal (2017) **xxx**, xxx–xxx

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ORIGINAL ARTICLE

Heat transfer in wall jet flow of magnetic-nanofluids with variable magnetic field

N. Sandeep [a,*], **I.L. Animasaun** [b]

[a] *Department of Mathematics, VIT University, Vellore 632014, India*
[b] *Department of Mathematical Sci., Federal University of Technology, Akure, Ondo State, Nigeria*

Received 20 September 2016; revised 1 December 2016; accepted 21 December 2016

KEYWORDS

MHD;
Al alloys 7072 and 7075;
Nanofluid;
Thermal radiation;
Convection

Abstract This study reports the enhanced heat transfer of electrically conducting magnetic-nanofluids with thermal radiation and inclined magnetic field effects. We consider water as a base fluid embedded with the two different types of aluminum alloy nanoparticles namely AA 7072 and AA 7075. AA 7072 is a special type of heat treatable aluminum alloy with 98% *Al* and 1% of *Zn* with the additives such as *Si*, *Fe* and *Cu*. Similarly, AA 7075 contains 90% *Al*, 5–6% *Zn*, 2–3% *Mg*, 1–2% *Cu* with the additives such as *Si, Fe* and *Mn*. Numerical results are explored with the aid of R-K and Newton's techniques. Results are depicted diagrammatically and discussed on the common profiles of interest (velocity and temperature). The heat transfer rate of water-AA 7075 nanofluid is significantly high when compared with the rate of heat transfer of water-AA 7072 nanofluid.

1. Introduction

Aluminum alloys have been very important in aerospace manufacturing. In particular, the aluminum alloys such as 7072 and 7075 are very useful in transport applications such as aviation, marine and automotive, which are also used in manufacturing of bicycle equipment, glider aircrafts and rock climbing equipment. External magnetic fields are capable to regulate the thermal and physical nature of the nanofluids. In particular, inclined magnetic fields are useful to vary the momentum and heat transfer of the flow by controlling the resistive force at different angles. Thermal radiation has variety of applications in heating/cooling devises and manufacturing industrial processing.

Aluminum alloy 7075 was developed by Japanese company in 1943, for production of air frame in Japanese navy [1]. The wall jet flow is developed when the fluid is blown tangentially along a wall. The detailed description on turbulent wall jet modeling and applications was given by [2]. A numerical computations and methods of wall jet flow and its engineering applications were initially addressed by Rossi [3]. A rise in heat transfer with the suspension of the nano meter sized solid particles was observed by Choi and Eastman [4], and found a gradual enhancement in the temperature field of the base fluid by suspending the nanoparticles and named the mixed solvent as nanofluid. The heat transfer characteristics of alloys were theoretically explained by Abramenko et al. [5]. The entry level behavior of laminar step flow was numerically investigated by Barton [6]. Thermal and physical properties of liquid and solid titanium based alloys were proposed by Boivineau et al. [7].

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[*] Corresponding author.

E-mail addresses: dr.nsrh@gmail.com (N. Sandeep), anizakph2007@gmail.com (I.L. Animasaun).

Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.12.019
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Please cite this article in press as: N. Sandeep, I.L. Animasaun, Heat transfer in wall jet flow of magnetic-nanofluids with variable magnetic field, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2016.12.019

Nomenclature

u, v	velocity components along x and y
ρ_{nf}	density of the nanofluid,
μ_{nf}	dynamic viscosity of the nanofluid
σ_{nf}	electrical conductivity of nanofluid
B_0	magnetic field strength
T	fluid temperature
k_{nf}	thermal conductivity
$(\rho c_p)_{nf}$	heat capacitance of the nanofluid
k^*	mean absorption coefficient
γ	aligned angle
σ^*	Stefan-Boltzmann constant
q_r	radiative heat flux
ϕ	volume fraction of the nanoparticles
ρ_f, ρ_s	densities of the base fluid and solid nanoparticles
k_f, k_s	thermal conductivities of the base fluid and solid nanoparticles
σ_f, σ_s	electrical conductivities of the base fluid and solid nanoparticles
$(c_p)_f, (c_p)_s$	specific heat capacity of the base fluid and solid nanoparticles
Pr	Prandtl number
M	magnetic field parameter
R	radiation parameter
γ	aligned angle
T_w	wall temperatures
v_f	kinematic viscosity
Bi	Biot number
Re_x	Reynolds number
Nu_x	Nusselt number

The role of nanoparticle shape on the flow and heat transfer of alumina nanofluids was studied by Timofeeva and Dileep Singh [8]. Amaranatha Reddy et al. [9] studied the impact of manganese doping magnetic properties of zinc and chromium nanoparticles.

The thermal and physical properties of high temperature alloys by making use of the thermal analysis were determined by Saari et al. [10]. A Mathematical model for energy transfer in alloys with the energy conservation equation was discussed by Abramenko et al. [11]. In this study they proposed exact solutions for the liquid and solid phases with effective vales of the heat capacities. The influence of aluminum based optical properties of zinc nanoparticles was experimentally studied by Amaranatha Reddy et al. [12]. The researchers [13–15] illustrated the magnetic field effects on nanofluid flows over a channel. Sulochana and Sandeep [16] studied the magnetohydrodynamic nanofluid flow past a permeable variable thickness sheet. Recently, the researchers [17,18], investigated the heat transfer characteristics of the wall jet flow by considering the various physical aspects.

Raju and Sandeep [19] numerically investigated the MHD non-Newtonian flow with Soret and Dufour effects. The convective heat transfer of MHD jet flow was numerically investigated by Zaidi and Mohyuddin [20]. The effect of variable magnetic field on unsteady magnetohydrodynamic flow over impulsively moving geometries was analytically and numerically studied by the authors [21,22]. Effect of Brownian movement on Al-water nanofluid with slip effects was numerically investigated by Malvandi and Ganji [23]. Buoyancy and radiation effects on micropolar nanofluid over a vertical surface were discussed by Ul Haq et al. [24]. Heat transfer in mixed convective flow of alumina nanofluid over a vertical micro channel was studied by Malvandi and Ganji [25].

Heat and mass transfer behavior of nanofluid flow past rotating parallel plates was numerically investigated by Mohyud-Din et al. [26]. Khan et al. [27] discussed the cross diffusion impact on chemically reacting viscous flow by considering the divergent and convergent channels. Ahmed et al. [28] investigated the heat transfer nature of the nanofluid flow over expanding and contracting walls. Convective heat transfer in magnetohydrodynamic flows by considering various geometries was theoretically analyzed by the researchers [29–32]. Khan et al. [33] studied the thermo diffusion effects on nanofluid flow past a stretching surface in porous medium. New buoyancy induced model for magnetohydrodynamic nanofluid flow was studied by the authors [34,35].

With the motivation of the above investigations, we make an attempt to analyze the free convective heat transfer of wall jet flow of water based electrically conducting radiative aluminum alloy nanofluids with variable magnetic field. Present work is unique due to the consideration of aluminum alloy nanoparticles namely AA 7072 and AA 7075 embedded in water. This helps to analyze the variation in heat transfer performance for small variation in copper percentage. In addition to this we considered external magnetic field applied at various angles. This helps to regulate the flow and thermal fields of the nanofluid.

2. Mathematical model

Two-dimensional fully developed laminar wall jet flow of a magnetic nanofluid over a vertical plate at temperature T_w parallel to x-axis is considered. An aligned magnetic field of strength B_0 is applied to the flow as depicted in Fig. 1. Viscous dissipation and the magnetic field induced are ignored in this study.

The equations govern the flow can be written as follows: Ref. [20]

2.1. Flow analysis

$$u_x + v_y = 0, \tag{1}$$

$$\rho_{nf}(uu_x + vu_y) = -p_x + \mu_{nf}(u_{xx} + u_{yy}) + \sigma_{nf}B^2(x)\sin^2\gamma u, \tag{2}$$

$$\rho_{nf}(uv_x + vv_y) = -p_y + \mu_{nf}(v_{xx} + v_{yy}), \tag{3}$$

with the boundary conditions

$$\begin{aligned} &u(0) = 0, \quad v(0) = 0, \\ &u(\infty) \to 0, \quad v(\infty) \to 0, \end{aligned} \tag{4}$$

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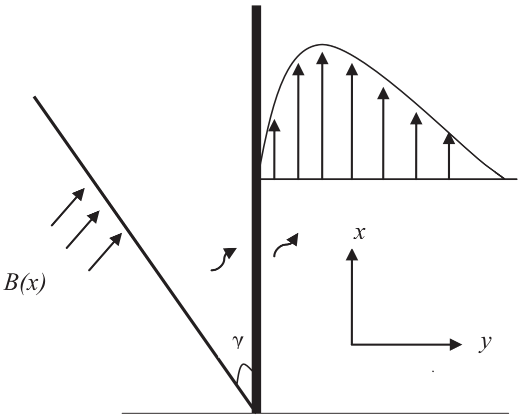

Figure 1 Physical model of the problem.

where the velocity components along x and y directions are u and v respectively, ρ_{nf}, μ_{nf} are the density and dynamic viscosity of the fluid, σ_{nf} is the electrical conductivity, p is the pressure applied, $B(x) = B_0 x^{-3/2}$ is the applied magnetic field and γ is the aligned angle. Here suffixes indicate the partial differentiation with respect to the specified independent variable.

For inside analysis, self-similarity transformation can be taken as

$$\eta = v^{-1/2}x^{-3/4}y, \quad \psi = 4v^{1/2}x^{1/4}f(\eta),$$
$$\theta = (T - T_\infty)/(T_w - T_\infty), \tag{5}$$

where ψ is a stream function such that $u = \psi_y$ and $v = -\psi_x$.

The nanofluid parameters are considered as (Ref. [35])

$$\left.\begin{aligned} &\rho_{nf} = \rho_f - \phi\rho_f + \phi\rho_s, \quad \mu_{nf} = \tfrac{\mu_f}{(1-\phi)^{2.5}},\\ &k_{nf} = \tfrac{(k_s+2k_f)-2\phi(k_f-k_s)}{(k_s+2k_f)+\phi(k_f-k_s)}k_f,\\ &(\rho c_p)_{nf} = (\rho c_p)_f - \phi(\rho c_p)_f + \phi(\rho c_p)_s,\\ &\sigma_{nf} = \sigma_f\left[1 + \tfrac{3(\sigma-1)\phi}{(\sigma+2)-(\sigma-1)\phi}\right], \quad \sigma = \tfrac{\sigma_s}{\sigma_f}, \end{aligned}\right\} \tag{6}$$

where ϕ is the nanoparticle volume fraction, ρ_f, ρ_s are the densities, k_f, k_s are the effective thermal conductivities, σ_f, σ_s are the electrical conductivities, and $(c_p)_f, (c_p)_s$ are the specific heat capacities of the fluid and solid particles respectively.

By making use of Eqs. (5) and (6), Eqs. (2) and (3) transformed as

$$\left(\frac{1}{(1-\phi)^{2.5}}\right)f''' + \left(1 - \phi + \phi\left(\frac{\rho_s}{\rho_f}\right)\right)(ff'' + 2f'^2)$$
$$- M\left(1 + \frac{3(\sigma-1)\phi}{(\sigma+2)-(\sigma-1)\phi}\right)f' = 0, \tag{7}$$

with the transformed boundary conditions

$$f(0) = 0, \quad f'(0) = 0, \quad f(\infty) \to 1, \tag{8}$$

where $M = B_0^2/\rho_f$ is the Hartmann number.

2.2. Thermal transport

The equation of energy with thermal radiation can be expressed as

$$(\rho c_p)_{nf}(uT_x + vT_y) = k_{nf}(T_{xx} + T_{yy}) + (16\sigma^* T_\infty^3/3k^*)(q_r)_y, \tag{9}$$

with the conditions

$$\begin{aligned} &-T_y = h_f(x)(T_w - T)/k_f \quad at\ y = 0,\\ &T \to T_\infty, \quad as\ y \to \infty, \end{aligned} \tag{10}$$

where k_{nf} represent the thermal conductivity, $(\rho c_p)_{nf}$ represent the heat capacitance of the nanofluid, q_r is the radiative heat flux, and σ^* and k^* are the Stefan-Boltzmann and mean absorption coefficients.

By using Eqs. (5) and (6), Eq. (9) transformed as follows

$$\left(\frac{k_{nf}}{k_f} + \frac{4}{3}R\right)\theta'' + Pr\left(1 - \phi + \phi\left(\frac{(\rho c_p)_s}{(\rho c_p)_f}\right)\right)f\theta' = 0, \tag{11}$$

with the transformed conditions

$$\begin{aligned} &\theta'(\eta) = -Bi(1 - \theta(\eta)) \quad at\ \eta = 0,\\ &\theta(\eta) \to 0, \quad as\ \eta \to \infty, \end{aligned} \tag{12}$$

where Bi is the Biot number, $Pr = v_f/\alpha_f$ is the Prandtl number.

The physical quantities of engineering interest, the local Nusselt number Nu_x is given as

$$Nu_x = \frac{k_{nf}xq_w}{k_f(T_w - T_\infty)}, \quad \text{Where } q_w = -k_f\left(\frac{\partial T}{\partial y}\right)\bigg|_{y=0}$$

$$Re_x^{-\frac{1}{2}}Nu_x = -\frac{k_{nf}}{k_f}\theta'(0), \tag{13}$$

where $Re_x = \frac{u_w^{1/2}x^{1/2}}{v}$ is the local Reynolds number.

3. Results and discussion

The nonlinear ODE's Eqs. (9) and (11) with the conditions of Eqs. (10) and (12) are solved using R-K and Newton's methods. For computation purpose, we adopted the pertinent parameter values as $Pr = 6.8$, $M = R = 5$, $\phi = 0.1$, $Bi = 0.8$, $\gamma = \pi/3$. Graphical results reveal the effect of various pertinent parameters on common profiles (velocity and temperature) of interest. Table 1 displays the thermo physical properties of the water and aluminum alloys.

From Figs. 2-4, it is evident that the boosting values of the aligned angle depreciate the momentum boundary layer and heat transfer rate, and encourage the thermal filed of the flow. Physically, rising values of the aligned angle improve the applied magnetic field strength. These cause to develop the resistive force called drag force, which works opposite direction to the flow. This may be the reason for reduction in the momentum boundary layer and enhancement in the thermal boundary layer. We also observed an interesting result that

Table 1 Thermal and physical properties.

Thermo physical properties	H_2O	AA7075	AA7072
ρ (kg/m^3)	997.1	2810	2720
c_p (J kg^{-1} K^{-1})	4179	960	893
k (W m^{-1} K^{-1})	0.613	173	222
σ (S/m)	0.05	26.77×10^6	34.83×10^6

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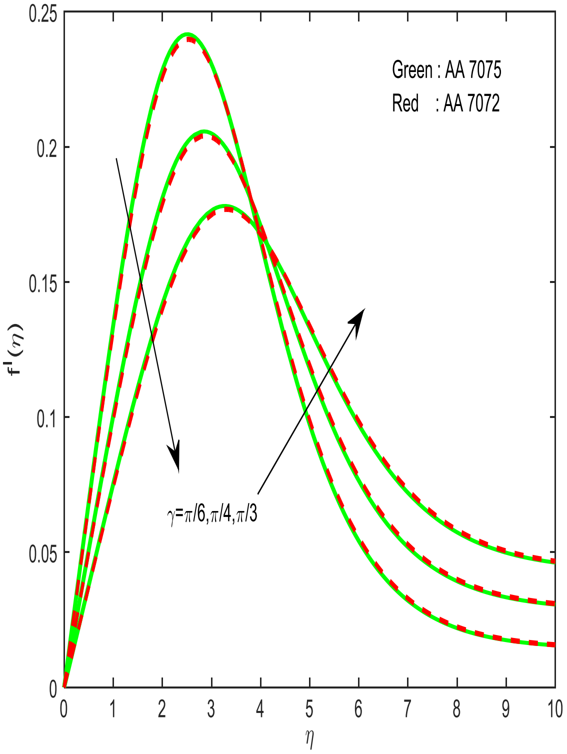

Figure 2 Effect of γ on velocity field.

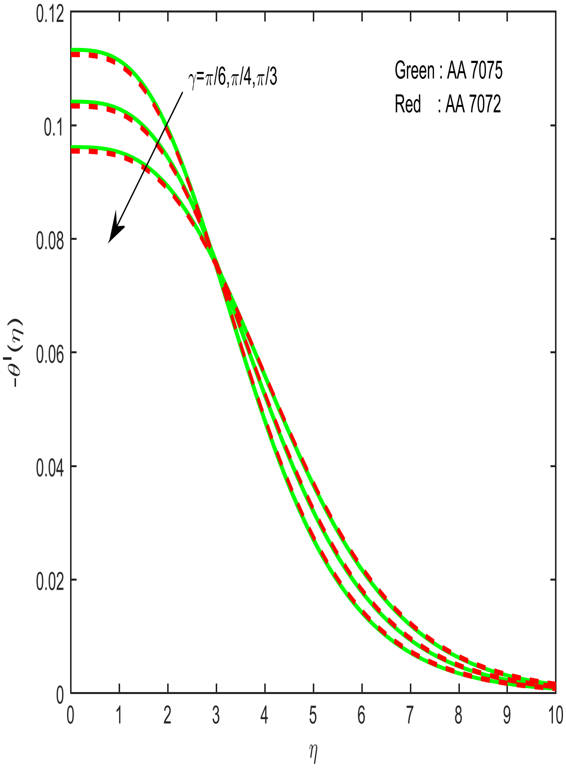

Figure 4 Effect of γ on local Nusselt number.

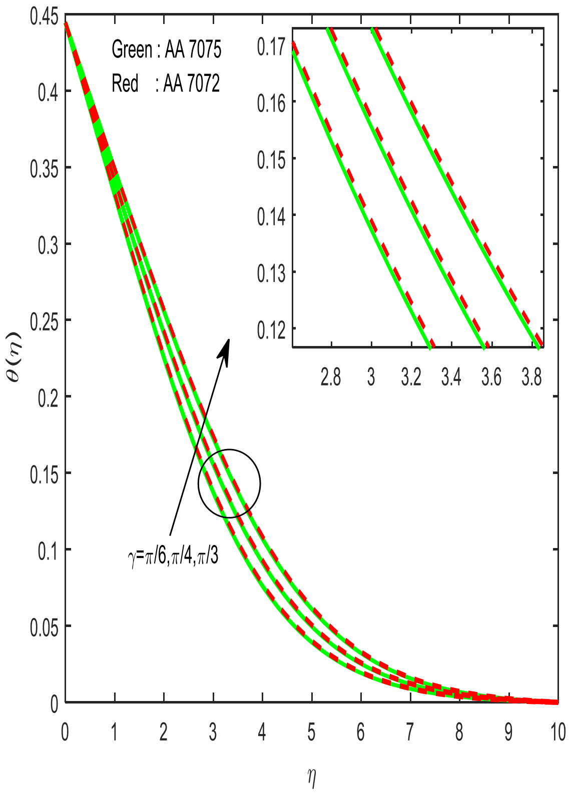

Figure 3 Effect of γ on temperature field.

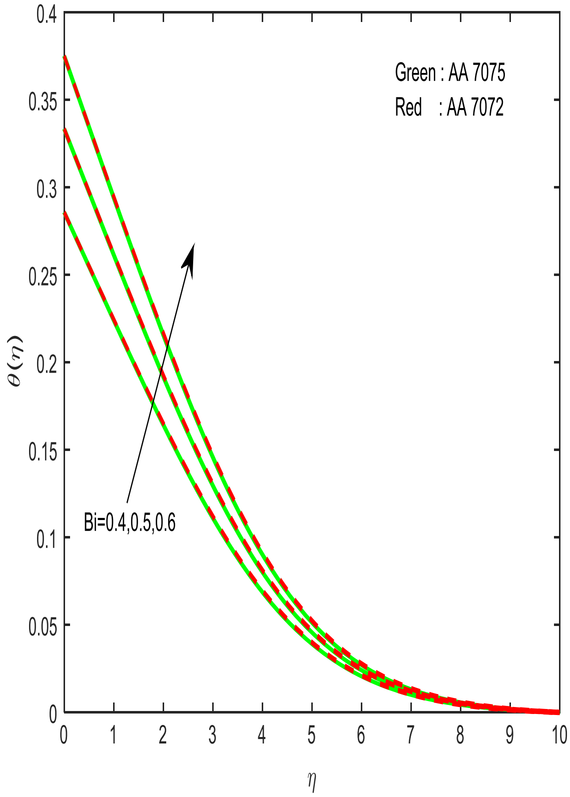

Figure 5 Effect of *Bi* on temperature field.

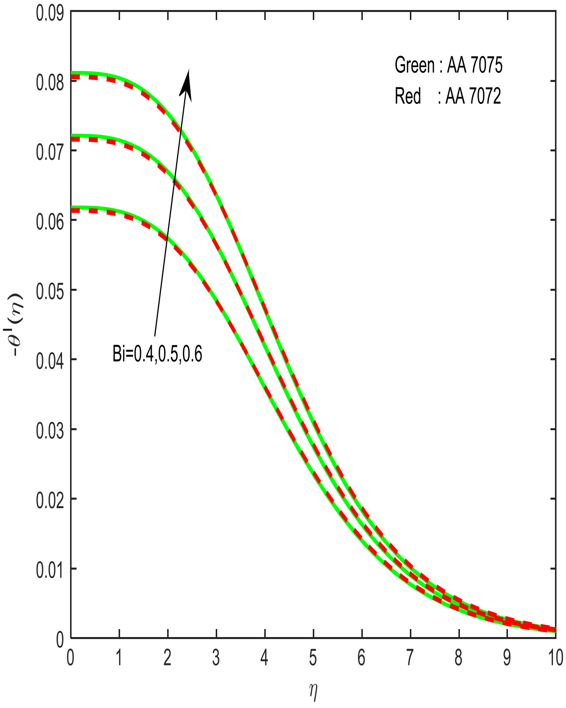

Figure 6 Effect of *Bi* on local Nusselt number.

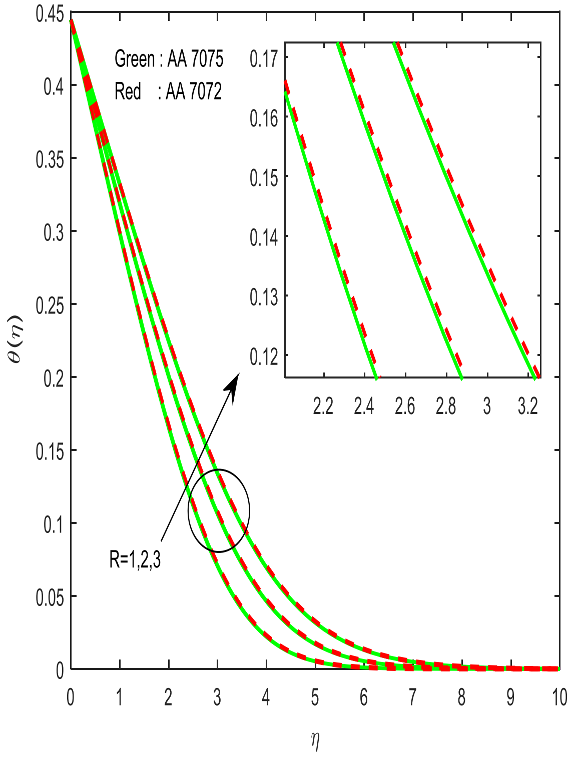

Figure 7 Effect of *R* on temperature field.

the thermal and momentum boundary layers of water-AA7072 nanofluid are highly influenced by strengthening the magnetic field. This concludes that the high electrical conductivity of AA7072 alloy causes to develop the induced magnetic field.

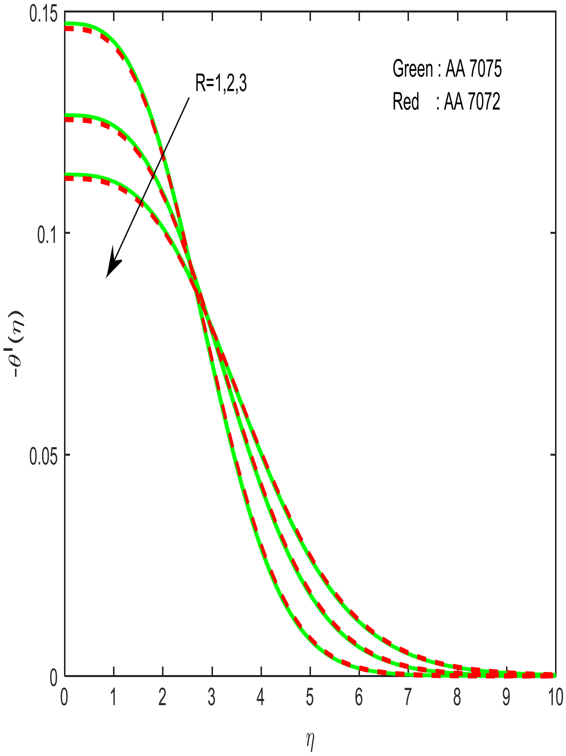

Figure 8 Effect of *R* on local Nusselt number.

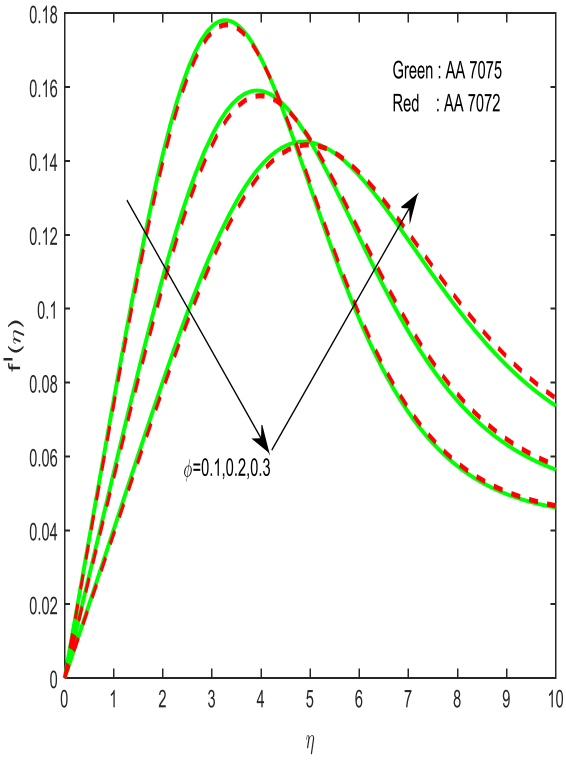

Figure 9 Effect of ϕ on velocity field.

Figs. 5 and 6 illustrate the effect of Biot number on thermal transport and local Nusselt number. Increasing value of the Biot number enhances the fluid temperature along with the

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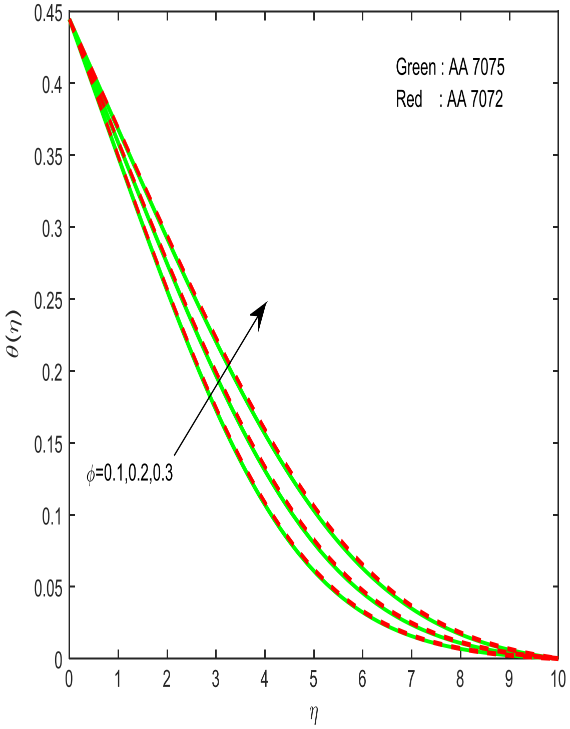

Figure 10 Effect of ϕ on temperature field.

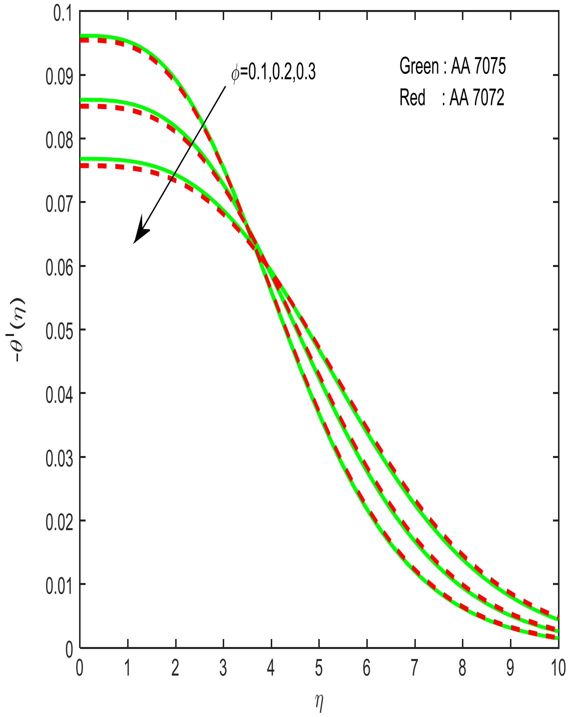

Figure 11 Effect of ϕ on local Nusselt number.

rate of heat transfer of both nanofluids. Physically, Biot number has tendency to boost the temperature difference between the particles. This leads to enhance the temperature field. It is also evident that the heat transfer is significantly high in water-AA7075 nanofluid when compared with water-AA7072 nanofluid.

Table 2 Validation of the present results under special and limited case.

η	Zaidi and Mohyuddin [20]	Present results
0.5	0.1105	0.110512
1.0	0.2123	0.212301
1.5	0.2865	0.286511

Table 3 Validation of the present results for various numerical techniques.

ϕ	Bvp4c	Bvp5c	RKS	RKN
0.1	0.09876320	0.09876320	0.09876320	0.0987632012
0.2	0.08764321	0.08764321	0.08764321	0.0876432121
0.3	0.07432516	0.07432516	0.07432516	0.0743251620

Figs. 7 and 8 display the thermal radiation effect on temperature and heat transfer rate of both nanofluids. A rise in the temperature profiles and suppress in the heat transfer rate is noticed for boosting values of R. Physically, rising values of the radiation cause to release the additional energy to the flow, which causes to develop the temperature filed. It is also observed that the thermal boundary layer of water-AA7075 effectively enhances while compared with water-AA7072.

From Figs. 9–11, it is evident that the increasing values of ϕ enhance the temperature field and decline the velocity field along with the reduced Nusselt number. This may be due to the increased thermal conductivity for rising values of ϕ. We validated the present results and found a good agreement, by considering the additional effects presented by Zaidi and Mohyuddin [20] which is depicted in Table 2. Numerical results are also validated by comparing with various numerical approaches, which are depicted in Table 3.

4. Conclusions

This study presents a convective heat transfer of radiative wall jet flow of a water based aluminum alloy nanofluids with inclined magnetic field and electrical conductivity. We consider water as a base fluid embedded with the two different types of aluminum alloy nanoparticles namely AA 7072 and AA 7075 and results are explored numerically. The findings are as follows:

- Aligned magnetic angle strengthens the applied magnetic field.
- Heat transfer rate is high in water-AA7075 nanofluid when equated with the water-AA7072 nanofluid.
- Variation in aluminum percentage makes the thermal and flow fields are non-uniform.
- Biot number regulates the heat transfer rate of both nanofluids.
- Electrical conductivity of water-AA7075 nanofluid is high when compared with the water- AA7072 nanofluid.
- This study is very useful for manufacturing industries especially in aerospace engineering.

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Please cite this article in press as: N. Sandeep, I.L. Animasaun, Heat transfer in wall jet flow of magnetic-nanofluids with variable magnetic field, Alexandria Eng. J. (2017), http://dx.doi.org/10.1016/j.aej.2016.12.019