



Available online at www.sciencedirect.com



Journal of the Nigerian Mathematical Society

Journal of the Nigerian Mathematical Society 35 (2016) 48-65

www.elsevier.com/locate/jnnms

# Influence of chemical reaction, radiation and rotation on MHD nanofluid flow past a permeable flat plate in porous medium

J.V. Ramana Reddy<sup>a</sup>, V. Sugunamma<sup>a,\*</sup>, N. Sandeep<sup>b</sup>, C. Sulochana<sup>b</sup>

<sup>a</sup> Department of Mathematics, S.V. University, Tirupati-517502, India <sup>b</sup> Department of Mathematics, Gulbarga University, Gulbarga-585106, India

Received 13 March 2015; received in revised form 16 August 2015; accepted 22 August 2015 Available online 15 September 2015

#### Abstract

In this paper we investigated an unsteady free convection flow of a nanofluid bounded by a moving vertical flat plate through porous medium in a rotating system with convective and diffusive boundary conditions. We considered two types of nanofluids namely Ag-water and TiO<sub>2</sub>-water. The governing equations are solved analytically by using perturbation technique. Finally the effects of various dimensionless parameters like magneticfield parameter, chemical reaction parameter, thermal radiation parameter, volume fraction of the nano particles and shape of the nano particles on velocity, temperature and concentration profiles along with the friction factor, local Nusselt and Sherwood numbers are discussed with the help of graphs. Comparisons of the present results made with the existed studies and found an excellent agreement under some special limited cases. Moreover, we observed that the rate of heat transfer in Ag-water nanofluid is higher than that of TiO<sub>2</sub>-water nanofluid and spherical shaped nano particles effectively enhances the heat transfer rate while compared with the cylindrical shaped nano particles.

© 2015 The Authors. Production and Hosting by Elsevier B.V. on behalf of Nigerian Mathematical Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Keywords: Nanofluid; Rotation; Radiation; MHD; Chemical reaction

#### 1. Introduction

Presently, convective heat transfer in nanofluids has wide range of applications, and plays a pivotal role in both sciences and engineering. They have many applications in almost every technology requiring heat transfer fluids (cooling or heating), solar energy, nuclear reactors etc. So, from the last few years the researchers of fluid dynamics are showing a keen interest in the study of nanofluids due to their applications in various fields. It is the fact that the commonly using fluids exhibits low thermal conductivity compared with the metals. So, it is required to mix both the fluid and metals (nano-sized) for increasing the heat transfer capability of the fluids. The suspension of nano-sized particles in the base fluid is called the nanofluid. The concept of nanofluids was developed by Choi [1] during an investigation of cooling technologies in Argonne National Lab. There are different types of nanofluids like process

\* Corresponding author.

http://dx.doi.org/10.1016/j.jnnms.2015.08.004

Peer review under responsibility of Nigerian Mathematical Society.

E-mail address: vsugunar@gmail.com (V. Sugunamma).

<sup>0189-8965/© 2015</sup> The Authors. Production and Hosting by Elsevier B.V. on behalf of Nigerian Mathematical Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

### Nomenclature

$u, v, w$ Velocity components of the fluid in $x, y$ and $z$ directions respectively $U_r$ Velocity characteristic $x, y, z$ Caterisain coordinates $t$ Time $\mathcal{Q}$ Rotating velocity of the system $\rho_f$ Density of the nanofluid $\rho_f$ Density of the solid nano particles $H_{aff}$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\psi_f$ Nume fraction of nano particles $\beta_{nff}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravityTTemperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $T_{\infty}$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_f$ Electrical conductivity of the solid nano particles $\sigma_{eff}$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the anofluid $\sigma_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific ent of anon particles $\sigma_{eff}$ Thermal diffusivity of the solid nano particles $\sigma_f$ Thermal diffusivity of the anofluid $\sigma_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific ent of anoparticles $\sigma$	1,01101	
$U_r$ Velocity characteristic $x, y, z$ Cartesian coordinates $t$ Time $\Omega$ Rotating velocity of the system $\rho_{rf}$ Density of the base fluid $\rho_r$ Density of the solid nano particles $\mu_{rf}$ Dynamic viscosity of the nanofluid $\psi_r$ Dynamic viscosity of the base fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_w$ Temperature of the fluid $T_w$ Temperature of the fluid near the plate $\beta_{rf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C_\infty$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_r$ Thermal diffusivity of the nanofluid $\alpha_r$ Thermal diffusivity of the nanofluid $\alpha_r$ Thermal conductivity of nanofluid $k_r$ <th>u, v, w</th> <th>Velocity components of the fluid in <math>x</math>, <math>y</math> and <math>z</math> directions respectively</th>	u, v, w	Velocity components of the fluid in $x$ , $y$ and $z$ directions respectively
$x, y, z$ Cartesian coordinates $t$ Time $\mathcal{Q}$ Rotating velocity of the system $\rho_{nf}$ Density of the base fluid $\rho_s$ Density of the solid nano particles $\mu_{nf}$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\psi_f$ Kinematic viscosity of the nanofluid $\psi_f$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravityTTemperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $T_{\infty}$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Concentration of the fluid $C_{\infty}$ Concentration of the fluid $C_{\infty}$ Concentration of the fluid fluid $C_{w}$ Concentration of the fluid fluid $C_{w}$ Concentration of the fluid $\sigma_n$ Electrical conductivity of the porous medium. $B_0$ Uniform magnetic field $\sigma_n$ Electrical conductivity of the solid nano particles $\alpha_nf$ Thermal diffusivity of the hase fluid $\sigma_s$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the base fluid $k_s$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the base fluid $k_$	$U_r$	
tTime $\mathcal{Q}$ Rotating velocity of the system $\rho_{nf}$ Density of the nanofluid $\rho_{f}$ Density of the solid nano particles $\mu_{nf}$ Dynamic viscosity of the nanofluid $\psi_{f}$ Dynamic viscosity of the abase fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_{w}$ Temperature of the fluid near the plate $\beta_{nf}^{*}$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C_{\infty}$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{rf}$ Electrical conductivity of the solid nano particles $\alpha_{rf}$ Thermal diffusivity of the base fluid $\alpha_{f}$ Thermal diffusivity of the base fluid $\alpha_{f}$ Thermal diffusivity of the base fluid $\alpha_{f}$ Thermal conductivity of the solid nano particles $\alpha_{rf}$ Thermal conductivity of the base fluid $k_{f}$ Thermal conductivity of the solid nano particles $\alpha_{ff}$ Thermal conductivity of the base fluid $k_{f}$ Thermal conductivity of the solid nano particles $\alpha_{ff}$ Thermal conductivity of the solid nano particles $D_{ff}$ Dimensionel chemical reaction parameter $N_{c}$ Convective parameter $N_{f}$ <th>-</th> <th>•</th>	-	•
$Ω$ Rotating velocity of the system $ρ_{ff}$ Density of the base fluid $ρ_{f}$ Density of the solid nano particles $μ_{nf}$ Dynamic viscosity of the nanofluid $μ_{ff}$ Dynamic viscosity of the base fluid $φ$ Volume fraction of nano particles $β_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_w$ Temperature of the fluid $T_w$ Temperature of the fluid $T_w$ Temperature of the fluid $C_w$ Concentration of the fluid $\sigma_n$ Electrical conductivity of the porous medium. $B_0$ Uniform magnetic field $\sigma_n$ Electrical conductivity of the solid nano particles $\alpha_n f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the solid nano particles $D_B$ Chemical molecu		
$\rho_{nf}$ Density of the nanofluid $\rho_{f}$ Density of the solid nano particles $\mu_{nf}$ Dynamic viscosity of the nanofluid $\mu_{ff}$ Dynamic viscosity of the nanofluid $\mu_{ff}$ Dynamic viscosity of the nanofluid $\psi_{ff}$ Dynamic viscosity of the base fluid $\phi_{ff}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $\sigma_{\infty}$ Ambient concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $G_{\infty}$ Electrical conductivity of the parous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the solid nano particles $a_{nf}$ Thermal diffusivity of the nanofluid $\sigma_{f}$ Thermal diffusivity of the base fluid $\sigma_{f}$ Thermal conductivity of the solid nano particles $\mu_{ff}$ Thermal conductivity of the solid nano particles $\mu_{ff}$ Thermal conductivity of the base fluid $k_{f}$ Thermal conductivity of the base fluid $k_{f}$ Thermal conductivity of the base		
$\rho_f$ Density of the base fluid $\rho_r$ Density of the solid nano particles $\mu_{nf}$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the base fluid $\psi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_w$ Temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_w$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_nf$ Electrical conductivity of the solid nano particles $\alpha_nf$ Thermal diffusivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_nf$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_nf$ Thermal conductivity of the solid nano particles $D_nf$ Thermal conductivity of the solid nano particles $D_nf$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity <th></th> <th></th>		
$\rho_s$ Density of the solid nano particles $\mu_{rf}$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $\psi_f$ Kinematic viscosity of the base fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_w$ Temperature of the fluid expansion of the nanofluid due to concentration difference $B_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_w$ Concentration of the fluid $\sigma_f$ Electrical conductivity of the parous medium. $B_0$ Uniform magnetic field $\sigma_f$ Electrical conductivity of the base fluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_nf$ Thermal conductivity of the solid nano particles $D_mensioned chemical reaction parameterN_cConvective parameterq_rThermal conductivity of the solid nano particlesD_nffElectrical conductivity of the solid nano particles\sigma_fThermal conductivity of the solid nano particles<$	b	•
$\mu_{nf}$ Dynamic viscosity of the nanofluid $\mu_f$ Dynamic viscosity of the nanofluid $v_f$ Kinematic viscosity of the base fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid near the plate $\beta_{nf}^{*}$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C_{\infty}$ Concentration of the fluid near the plate $\beta_{nf}^{*}$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the base fluid $\sigma_f$ Electrical conductivity of the sale fluid $\sigma_f$ Electrical conductivity of the sale fluid $\sigma_f$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal conductivity of the sale fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_f$ Thermal conductivity of the sale fluid $k_f$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the s	b	
$\mu_f$ Dynamic viscosity of the nanofluid $v_f$ Kinematic viscosity of the base fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_nf$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the base fluid $k_f$ Thermal conductivity of the solid nano particles $\beta_{nf}$ Thermal conductivity of the solid nano particles $\beta_{nf}$ Thermal conductivity of the solid nano particles $\beta_{nf}$ Thermal conductivity of the base fluid $k_f$ Thermal		
$v_f$ Kinematic viscosity of the base fluid $\phi$ Volume fraction of nano particles $\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature difference $g$ Acceleration due to gravity $T$ Temperature of the fluid $T_w$ Temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the solid nano particles $a_{nf}$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the solid nano particles $q_r$ The radiative heat term $Q$ Thermal conductivity of the solid nano particles $k_{nf}$ Thermal conductivity of the solid nano particles $k_{nf}$ Thermal conductivity of the solid nano particles $k_{nf}$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $N_d$ Dimensionless temperature $\psi$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $N_d$ <	5	
$φ' Volume fraction of nano particles βnf Coefficient of thermal expansion of the nanofluid due to temperature difference g Acceleration due to gravity T Temperature of the fluid T∞ Ambient temperature of the fluid T∞ Temperature of the fluid near the plate β*nf Coefficient of thermal expansion of the nanofluid due to concentration difference C Concentration of the fluid C∞ Ambient concentration of the fluid C∞ Concentration of the fluid C∞ Concentration of the fluid near the plate k Dimensioned permeability of the porous medium. B0 Uniform magnetic field σnf Electrical conductivity of the nanofluid σs Electrical conductivity of the sase fluid (cp)nf Specific heat capacity of the nanofluid aff Thermal diffusivity of the nanofluid aff Thermal diffusivity of the nanofluid aff Thermal diffusivity of nanofluid aff Thermal conductivity of the sase fluid (cp)nf Specific heat capacity of the nanofluid at constant pressure qr The radiative heat term Q The temperature dependent volumetric rate of heat source knf Thermal conductivity of the solid nano particles DB Chemical molecular diffusivity k1 Dimensioned chemical reaction parameter Nc Convective parameter Nc Convective parameter V Velocity of the fluid θ Dimensionless temperature \psi Dimensionless temperature\psi Dimensionless temperature\psi Dimensionless temperatureK$ Dimensionless heat source parameter K Dimensionless heat source parameter K Dimensionless heat source parameter K Dimensionless heat source parameter K Dimensionless chemical reaction parameter K Dimensionless chemical reaction parameter K Dimensionless heat source parameter	-	
$\beta_{nf}$ Coefficient of thermal expansion of the nanofluid due to temperature differencegAcceleration due to gravityTTemperature of the fluid $T_{\infty}$ Ambient temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the platekDimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the anofluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the base fluid $k_f$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_i$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless temperature $\psi$ Dimensionless heat source parameter $R$ Rotational parameter $R$ Dimensionless heat source p		
gAcceleration due to gravityTTemperature of the fluid $T_{\infty}$ Ambient temperature of the fluid $T_w$ Temperature of the fluid near the plate $g_n f$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_n f$ Electrical conductivity of the base fluid $\sigma_f$ Electrical conductivity of the solid nano particles $a_n f$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_n f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_i$ Dimensioned permeature dependent volumetric rate of heat source $k_n f$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_i$ Dimensionelse temperature $N_c$ Convective parameter $N_c$ Convective parameter $N_c$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless concentration $S$ Suction/injection par	-	
$T$ Temperature of the fluid $T_{\infty}$ Ambient temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_{w}$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_s$ Electrical conductivity of the nanofluid $\alpha_f$ Thermal diffusivity of the nanofluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $M$ Magnetic field parameter $R$ Rotational parameter $R$ Dimensionless temperature $f$ Dimensionless permeability parameter of the porous medium $Q$ Iffusive parameter $R$ Dimensionless ha	$\beta_{nf}$	
$T_{\infty}$ Ambient temperature of the fluid $T_w$ Temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the base fluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $M$ Magnetic field parameter $M$ Magnetic field parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless chemical reaction parameter $F$ Themsionless chemical reaction parameter $F$ Dimensionless permeability parameter of the porous medium $Q$ Diffusive parameter $K$ Dimensionless permeability parameter of the porous medium $Q$ Diffusive parameter $K$ <th></th> <th></th>		
$T_w$ Temperature of the fluid near the plate $\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_\infty$ Ambient concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the base fluid $\sigma_r$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $M$ Magnetic field parameter $M$ Magnetic field parameter $K$ Dimensionless temperature $f$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	-	-
$\beta_{nf}^*$ Coefficient of thermal expansion of the nanofluid due to concentration difference $C$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid $C_w$ Concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the base fluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless temperature $\psi$ Dimensionless temperature $M$ Magnetic field parameter $R$ Rotational parameter $R$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Themal radiation parameter $K_r$ Dimensionless chemical reaction parameter		-
$C_{2}^{(r)}$ Concentration of the fluid $C_{\infty}$ Ambient concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_f$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $K$ Dimensionless heat source parameter $F$ Thermal radiation parameter $F$ Dimensionless chemical reaction parameter		
CConcentration of the fluid $C_{\infty}$ Ambient concentration of the fluid near the plate $k$ Dimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_f$ Specific heat capacity of the base fluid $\sigma_s$ Electrical conductivity of the base fluid $\sigma_f$ Thermal diffusivity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_1$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	$\beta_{nf}^*$	Coefficient of thermal expansion of the nanofluid due to concentration difference
$C_w$ Concentration of the fluid near the platekDimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $K_r$ Dimensionless chemical reaction parameter	C	Concentration of the fluid
kDimensioned permeability of the porous medium. $B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the base fluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the base fluid $k_f$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $W$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $R$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless chemical reaction parameter	$C_\infty$	Ambient concentration of the fluid
$B_0$ Uniform magnetic field $\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the nanofluid at constant pressure $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	$C_w$	
$\sigma_{nf}$ Electrical conductivity of the nanofluid $\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	k	Dimensioned permeability of the porous medium.
$\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	$B_0$	Uniform magnetic field
$\sigma_f$ Electrical conductivity of the base fluid $\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter	$\sigma_{nf}$	Electrical conductivity of the nanofluid
$\sigma_s$ Electrical conductivity of the solid nano particles $\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K$ Dimensionless heat source parameter $K$ Dimensionless chemical reaction parameter	-	Electrical conductivity of the base fluid
$\alpha_{nf}$ Thermal diffusivity of the nanofluid $\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $K$ Dimensionless chemical reaction parameter	-	
$\alpha_f$ Thermal diffusivity of the base fluid $(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K_r$ Dimensionless chemical reaction parameter		
$(c_p)_{nf}$ Specific heat capacity of the nanofluid at constant pressure $q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K_r$ Dimensionless chemical reaction parameter	-	•
$q_r$ The radiative heat term $Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K_r$ Dimensionless chemical reaction parameter	-	
$Q$ The temperature dependent volumetric rate of heat source $k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K_r$ Dimensionless chemical reaction parameter		
$k_{nf}$ Thermal conductivity of nanofluid $k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter	-	
$k_f$ Thermal conductivity of the base fluid $k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $K_r$ Dimensionless chemical reaction parameter	. –	
$k_s$ Thermal conductivity of the solid nano particles $D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter	•	
$D_B$ Chemical molecular diffusivity $k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		
$k_l$ Dimensioned chemical reaction parameter $N_c$ Convective parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		
$N_c$ Convective parameter $N_d$ Diffusive parameter $N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		
$N_d$ Diffusive parameter $V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter	-	
$V$ Velocity of the fluid $\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter	-	
$\theta$ Dimensionless temperature $\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		
$\psi$ Dimensionless concentration $S$ Suction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		•
SSuction/injection parameter $M$ Magnetic field parameter $R$ Rotational parameter $K$ Dimensionless permeability parameter of the porous medium $Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter	-	
MMagnetic field parameterRRotational parameterKDimensionless permeability parameter of the porous mediumQ_HDimensionless heat source parameterFThermal radiation parameterKrDimensionless chemical reaction parameter		
<ul> <li>R Rotational parameter</li> <li>K Dimensionless permeability parameter of the porous medium</li> <li>Q<sub>H</sub> Dimensionless heat source parameter</li> <li>F Thermal radiation parameter</li> <li>Kr Dimensionless chemical reaction parameter</li> </ul>		
<ul> <li><i>K</i> Dimensionless permeability parameter of the porous medium</li> <li><i>Q<sub>H</sub></i> Dimensionless heat source parameter</li> <li><i>F</i> Thermal radiation parameter</li> <li><i>Kr</i> Dimensionless chemical reaction parameter</li> </ul>		
$Q_H$ Dimensionless heat source parameter $F$ Thermal radiation parameter $Kr$ Dimensionless chemical reaction parameter		
FThermal radiation parameterKrDimensionless chemical reaction parameter		
<i>Kr</i> Dimensionless chemical reaction parameter		1
		•
Pr Prandtl number		
	Pr	Prandtl number

Download English Version:

## https://daneshyari.com/en/article/4646428

Download Persian Version:

https://daneshyari.com/article/4646428

Daneshyari.com