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Numerical Study of Nonlinear Convective Heat Transfer Flow of Metal Oxide Nanoparticle TiO_2-Enhanced Fluid between Two Concentric Cylinders with Aggregation of Nanoparticles

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Abstract

The utilization of nanofluid is one of the most used techniques for improving heat transfer in applications like heat exchangers, heat storage systems, mining and nuclear power plants. Because of high thermal conditions, the density relation of the working fluids may not be linear, therefore, an analysis is conducted on the quadratic convection of nanofluid flow in a porous annulus region considering an inclination. The phenomenon of temperature-dependent viscosity on the flow, kinematics of nanoparticle aggregation, and heat transport phenomenon with Exponential Space-Related Heat Source (ESHS) and a Temperature-Related Heat Source (THS) are considered. The governing equations are solved numerically. The influence of key parameters is analyzed using 2D and 3D graphs.

Keywords: *Convective Boundary Condition, Metal Oxide Nanoparticle, Nanoparticle Aggregation, Reynold's Model Viscosity*

1.0 Introduction

Fluids play an important role in heat transfer techniques in industrial applications like cooling systems in transportation, buildings, petrochemical industries, and other processing plants. Heat transfer can be engineered by adding metal oxide nanoparticles (like TiO_2,AgO_2,CuO) into fluids like water (H_2O), ethylene glycol ($C_2H_6O_2$), etc. This instigated the study of nanofluid flow in heat transfer problems and the study was pioneered by Choi and Eastman[1]. Subsequently, numerous investigations have been conducted on the dynamics of nanofluids. Among many nanoparticles, TiO_2 stands higher because of the following two natures: 1. It is chemically stable 2. Ecofriendly and has low-cost production. Ethylene glycol is used as a base liquid this is due to its anti-freezing property. The rheological properties of the above-mentioned nanofluid were studied by Chen *et al.*[2]. Since the improvement of thermal conductivity in nanofluids is the major focus of the researchers, by using the type, shape, and properties of the nanomaterial one can study the rheological properties of the aggregated nanoparticles. Wolthers *et al.* [3] employed this approach to model the relative viscosity of the nanomaterial. Later many kinds of research on the aggregation of nanoparticles have been conducted by various researchers[4-7].

Most of the problems concerning flow are through cylinders. In this context, many works have been conducted by various researchers using cylindrical geometry. Bourne and Elliston[8] examined heat transfer on moving fibre through an axially symmetric boundary layer by neglecting transverse vibrations that fibre may

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undergo. Karnis[9] investigated the thermal boundary layer on an isothermal cylinder using Kármán-Pohlhausen integral technique. Chamkha[10] considered the hydromagnetic flow of steady and laminar flow over a permeable cylinder and solved obtained governing equations using the similarity transformation technique and tri-diagonal finite-difference method. Shahzadi and Nadeem[11] studied heat transfer in the flow of nanofluid through an inclined annular duct. Oni[12] conducted a study on mixed convection flow in a vertical annulus filled with porous material by considering thermal radiation, a heat source. Thriveni and Mahanthesh[13] performed a numerical investigation and sensitivity computation on the flow of a hybrid nanofluid between two concentric cylinders by considering nonlinear convective heat transfer and irregular heat source.

The linear Boussinesq approximation, which assumes that density variations are linear, remains valid only when there is a minimal temperature difference. However, in applications such as various processing plants, combustion systems, and solar collectors, high temperatures are typically encountered. So considering Nonlinear Boussinesq Approximation (NBA) is suitable for such scenarios. In this regard, Goren[14] considered nonlinear density variations with temperature, and later Vajravelu and Shastri[15] conducted a study on free convection flow, examining both linear and quadratic approximations for density variations with temperature, as outlined below:

$$\rho(T) = \rho(T_w) + (T - T_w)\left(\frac{\partial \rho}{\partial T}\right)_w + \frac{1}{2!}(T - T_w)^2\left(\frac{\partial^2 \rho}{\partial T^2}\right)_w,$$

$$\Rightarrow \frac{\Delta \rho}{\rho} = -[(T - T_w)\beta_0 + (T - T_w)^2\beta_1]$$

here

$$\beta_0 = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_w \text{ and } \beta_1 = \frac{1}{2\rho}\left(\frac{\partial^2 \rho}{\partial T^2}\right)_w$$

Mahanthesh[16], investigated Quadratic Boussinesq approximation along with considering Quadratic thermal radiation on the flow of hybrid nanofluid.

It is well known that viscosity strongly depends on temperature, Dandapat *et al.*[17] considered variation viscosity in the form as follows:

$$\mu = \mu_0 e^{-\xi(T - T_0)} \quad \text{(a)}$$

where, μ_0 is the viscosity of the fluid at slit temperature T_0, ξ is the strength dependency between viscosity $\mu(T)$ and temperature (T). Megahed *et al.*[18] investigated the effect of variable fluid properties in the unsteady MHD fluid flow over a stretching sheet. It is worth studying the skinfriction coefficient (τ) and Nusselt number (Nu) parametrically with the help of a multiple regression model. . In this regard, several authors have performed multiple regression and obtained regression models for Nu and τ[19,20].

The focus of this paper is on a numerical and parametric investigation of quadratic convection in the context of nanofluid flow within an inclined porous annulus region. This study encompasses the examination of nanoparticle aggregation kinetics, and heat transport phenomena with the influence of ESHS and THS. Additionally, this work explores the effect of temperature-dependent viscosity on the flow, and key parameter significance is further assessed through regression analysis.

2.0 Mathematical Formulation

Consider the nonlinear convective flow of ethylene glycol with the immersion of titania TiO_2 nanoparticles in an inclined porous annular region. T_0 and T_w are the temperature at the outer boundary of the inner cylinder having radius *b* and the inner boundary of the outer cylinder having radius b respectively as in Figure 1. The problem is modelled based on the following assumptions:

- The cylindrical coordinate system is established for the model with '*r*' representing the radial direction and the 'z-axis' serving as the shared axis for both cylinders.
- The annular region is considered to have infinite length, which results in the flow being unaffected by changes in the z-coordinate.
- The fluid is Newtonian, incompressible, and the impact of viscous dissipation is not considered.
- NBA is assumed, and Darcy law is considered for the porous medium.
- THS and ESHS, aggregation kinematics of the nanoparticles are considered.

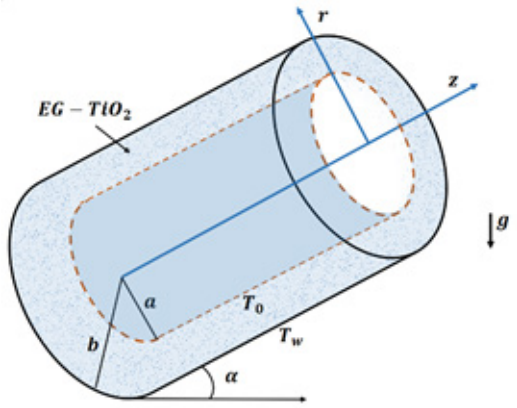


Figure 1. Physical representation of the problem.

- Variation of the viscosity is assumed as in equation (a).

Hence, based on the above assumptions, the governing equations take the following form [12,13]:

$$\frac{1}{\rho_{nl}}\frac{1}{r}\frac{d}{dr}\left(r\mu_{nl}(T)\frac{du}{dr}\right)+\frac{g}{\rho_{nl}}[(\rho\beta_0)_{nl}(T-T_0)+(\rho\beta_1)_l(T-T_0)^2]\cos(\alpha)-\frac{\mu_{nl}(T)u}{K\rho_{nl}}-\frac{1}{\rho_{nl}}\frac{dp}{dz}=0 \quad (1)$$

$$\frac{k_{nl}}{(\rho C_p)_{nl}}\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)\right]+\frac{Q_0}{(\rho C_p)_{nl}}(T-T_0)+\frac{T_w-T_0}{(\rho C_p)_{nl}}Q_e e^{-nr/a}=0 \quad (2)$$

Subjected to boundary conditions:

u=0, $T=T_0$ when r=a and

u=0, $T=T_w$ when r=b. (3)

Where u → velocity, T → temperature, ρ → density, k → thermal conductivity, K → permeability factor, C_p → heat capacitance, n → exponential index, g → acceleration due to gravity, Q_0,Q_E → THS, ESHS coefficients, α → angle of inclination, subscripts 0 denotes the outer boundary of the inner cylinder and w denotes the inner boundary of the outer cylinder, nl, l denotes nanofluid and base fluid.

The proposed phenomenological laws for the effective thermophysical properties of the nanofluid, considering the nanoparticles aggregation as suggested by Chen *et al.*[2] are outlined as follows:

$$\frac{\mu_{nl}}{\mu_l}=\mathbb{A}_1=\left(1-\frac{\phi_a}{\phi_m}\right)^{[\zeta]\phi_m}, \quad (4)$$

$$\frac{k_{nl}}{k_l}=\mathbb{A}_2=\frac{\left(\frac{k_a}{k_l}+2\right)+2\phi_a\left(\frac{k_a}{k_l}-1\right)}{\left(\frac{k_a}{k_l}+2\right)-\phi_a\left(\frac{k_a}{k_l}-1\right)} \quad (5)$$

$$\frac{\rho_{nl}}{\rho_l}=\mathbb{A}_3=(1-\phi_a)+\phi_a\frac{\rho_{np}}{\rho_l}, \quad (6)$$

$$\frac{(\rho c_p)_{nl}}{(\rho c_p)_l}=\mathbb{A}_4=(1-\phi_a)+\phi_a\frac{(\rho c_p)_{np}}{(\rho c_p)_l}, \quad (7)$$

$$\frac{(\rho\beta_0)_{nl}}{(\rho\beta_0)_l}=\mathbb{A}_5=\frac{(1-\phi_a)+\phi_a\frac{(\rho\beta_0)_{np}}{(\rho\beta)_l}}{(1-\phi_a)+\phi_a\frac{\rho_{np}}{\rho_l}}. \quad (8)$$

Where, $\phi_a=\phi\left(\frac{r_a}{r_p}\right)^{3-D}$ → effective nanoparticle volume fraction, $\frac{r_a}{r_p}$ → ratio of radii of aggregates and primary nanoparticles D→ fractal index, [ζ]→intrinsic viscosity. We take $\frac{r_a}{r_p}=3.34, \phi_m=0.605, D=1.8,$ and $[\zeta]=2.5$ (2),

$$k_a/k_l=\frac{1}{4}\left\{(3\phi_{in}-1)\frac{k_s}{k_l}+(3(1-\phi_{in})-1)+\left[\left((3\phi_{in}-1)\frac{k_s}{k_l}+(3(1-\phi_{in})-1)\right)^2+8\frac{k_s}{k_l}\right]^{\frac{1}{2}}\right\}\rightarrow$$

the ratio of aggregate thermal conductivity to the thermal conductivity of the base fluid, as determined by the Bruggeman model[21], $\phi_{in}=\left(\frac{r_a}{r_p}\right)^{D-3}$ → solid volume fraction of aggregates. The properties related to thermal and physical characteristics of the base fluid Ethylene Glycol and Titanium Dioxide are as follows:

Table 1. Thermophysical Properties of Ethylene Glycol and Titanium Dioxide Titania

	Ethylene Glycol	**Titanium Dioxide – Titania TiO_2**
Density ρ (kg/m^3)	1114	4250
Thermal Conductivity K (W/mk)	0.252	8.9538
Specific Heat c_p (j/kg K)	2415	686.2
Thermal expansion Coefficient (K^{-1})	0.00065	0.9 x 10^{-5}

3.0 Solution Procedure

Let define dimensionless quantities[12]

$$U = \frac{u}{u_0}, P = \frac{pa}{u_0 \nu_l}, \theta = \frac{T - T_0}{T_w - T_0}, R = \frac{r}{a}, Z = \frac{z}{a} \quad (9)$$

In view of equations (1) and (4) to (9), equations (1) to (3) are reduced to the following non-dimensional system of ordinary differential equations.

$$\mathbb{A}_1 e^{-\beta\theta}\left[U'' + \frac{1}{R}U' - U'\theta'\right] + Mc[\mathbb{A}_5\theta + Qc\theta^2]\cos\alpha - \frac{\mathbb{A}_1}{Da}e^{-\beta\theta}U - M = 0 \quad (10)$$

$$\frac{\mathbb{A}_2}{Pr}\left[\theta'' + \frac{1}{R}\theta'\right] + QT\theta + QEe^{-nR} = 0 \quad (11)$$

Here the prime denotes differentiation with respect to R. Subjected to boundary conditions:

U, θ=0 at R=1, U, θ=1 at R=λ (12)

The dimensionless Nusselt number and skin friction coefficients are defined as

$$\left.\begin{array}{c} Nu_1 = \mathbb{A}_2\theta'(1) \\ \tau_1 = \mathbb{A}_1 e^{-\beta\theta(1)}U'(1) \text{ at } R = 1 \\ Nu_\lambda = -\mathbb{A}_2\theta'(\lambda), \\ \tau_\lambda = -\mathbb{A}_1 e^{-\beta\theta(1)}U'(\lambda) \text{ at } R = \lambda \end{array}\right\} \quad (13)$$

Where,

$Qc = \frac{(\rho\beta_1)_l}{(\rho\beta_0)_l}(T_w - T_0) \rightarrow$ quadratic convection parameter,

$Da = \frac{K}{a^2} \rightarrow$ Darcy number,

$Mc = \frac{g(\rho\beta_0)_l a^2}{u_0\mu_l}(T_w - T_0) \rightarrow$ mixed convection parameter,

$QT = \frac{Q_0 a^2}{\nu_l(\rho C_p)_l}, QE = \frac{Q_e a^2}{\nu_l(\rho C_p)_l} \rightarrow$ THS, EHS parameter,

$Pr = \frac{(\mu C_p)_l}{k_l} \rightarrow$ Prandtl number (Pr is 150.4583333 for ethylene glycol), and

$\frac{dP}{dZ} = M \rightarrow$ constant (see (12)),

$Re = \frac{u_0 a}{\nu_l} \rightarrow$ Reynolds number,

$\beta = -B(T_w - T_0) \rightarrow$ variable viscosity parameter.

The obtained system (10)-(12) are solved using MAPLE which uses FDM with the Richardson extrapolation technique. The values of Nu_1 are compared with the values reported by (12) and observed excellent agreement (Table 2). Effects of various key parameters on velocity and temperature profiles are portrayed using 2D graphs. Influence on Nusselt number and skin friction coefficients by the key parameters are depicted by 3D surface plots.

4.0 Results and Discussions

The nature of velocity U(R) and temperature θ(R) profiles on variations of $0 \le \alpha \le \pi/4$, $0 \le \beta \le 0.4$, $0.1 \le Da \le 0.5$, $2 \le Mc \le 6$, $0.1 \le QE \le 0.2$ and $QT \in \{0.01, 0.02\}$ are captured using 2D graphs in Figure 2 to Figure 8. Throughout the calculations ϕ is taken to be 3%. An increase in α causes the least velocity dominated by the acceleration due to gravity, hence a decrease in velocity profiles can be observed in Figure 2. β corresponds to the variable viscosity, hence increase in the variable viscosity parameter decreases the

Table 2. Comparison of the values of present work with the available previous literature:

Da=0.1, M=0, Mc=50, α=0, Pr=1, QE = 0 = ϕ		
QT	**Nu_1 by [12]**	**Nu_1 in Present Work**
0.5	1.571404	1.571404
1.5	1.882604	1.882604
2.5	2.291116	2.291116

bulk viscosity causing an increase in velocity profiles can be observed in Figure 3.

The velocity field characteristics for various values of Da which correspond to porous permeability are graphed in Figure 4. Lower values of Da lower the permeability and higher values of Da lower the frictional drag forces results in an upsurge in velocity profiles are observed. Mc corresponds to the ratio of buoyancy to inertial force, an increase in Mc increases the buoyancy force which results in enhanced flow (Figure 5). Qc also shows the same nature on the velocity field due to an increase in buoyancy force (Figure 6). Enhancement of QE and QT on temperature and velocity field are depicted in Figure 7 and Figure 8. The mechanism of ESHS and THS boosts the thermal pattern by adding up the extra heat in the liquid and also a notable improvement in the velocity field is also observed.

Figure 9 – Figure 12 are the 3D surface plots that portray the impact of QE,QT on Nusselt numbers Nu_1,Nu_λ and skin frictions τ_1,τ_λ respectively. Increase in Nu_1,Nu_λ,τ_1,τ_2 is observed for the large values of QE and QT.

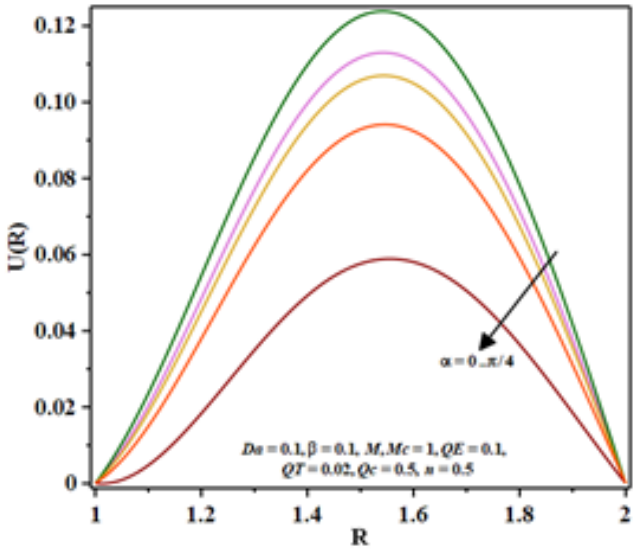


Figure 2. α's influence on Velocity profiles.

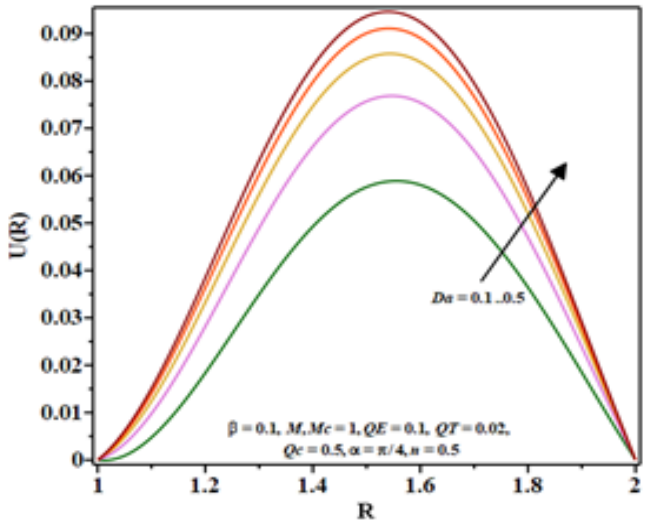


Figure 4. Da's influence on Velocity profiles.

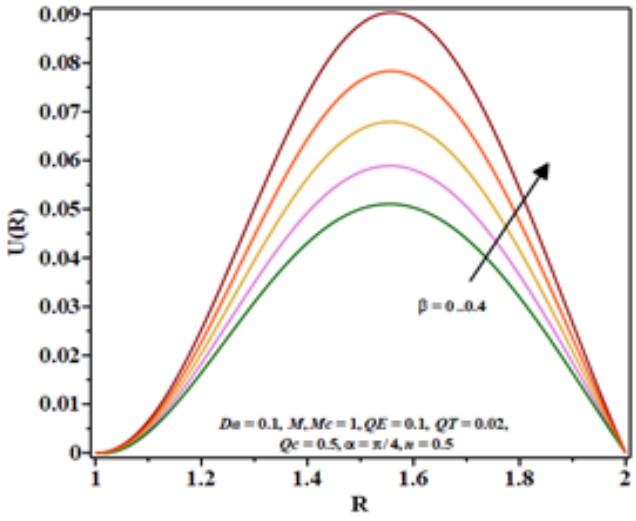


Figure 3. . β's influence on Velocity profiles.

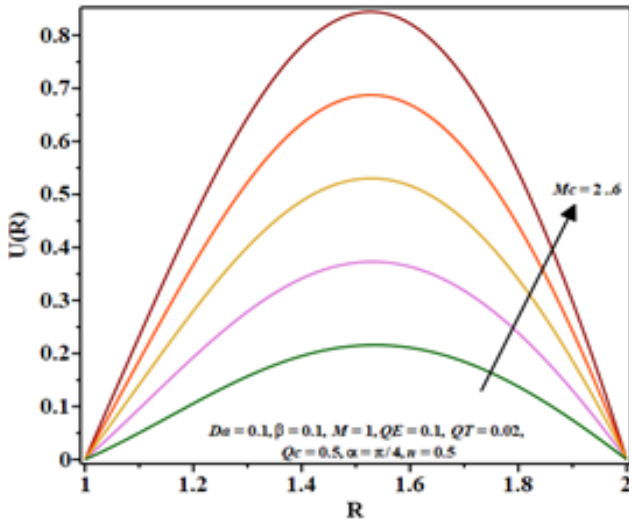


Figure 5. Mc's influence on Velocity profiles.

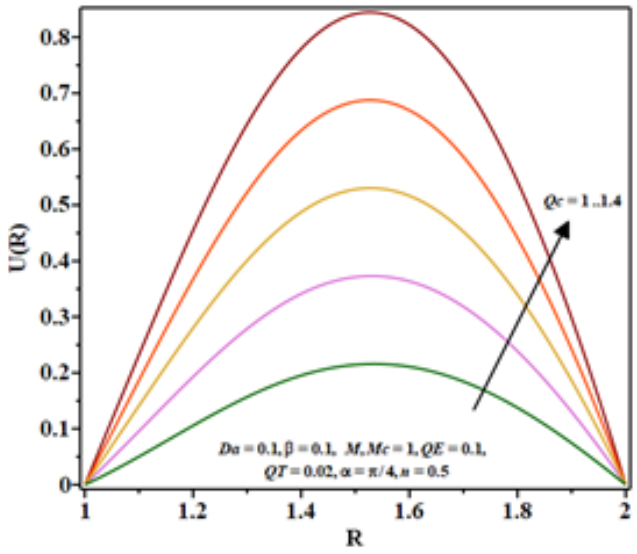


Figure 6. Qc's influence on Velocity profiles.

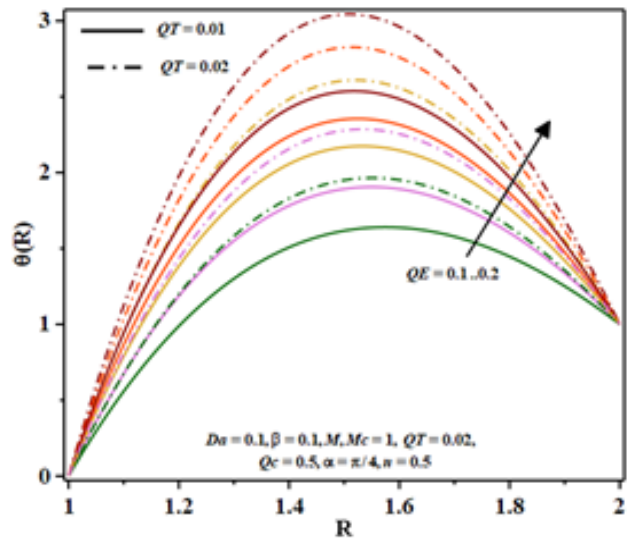


Figure 8. QE's influence on Temperature profiles.

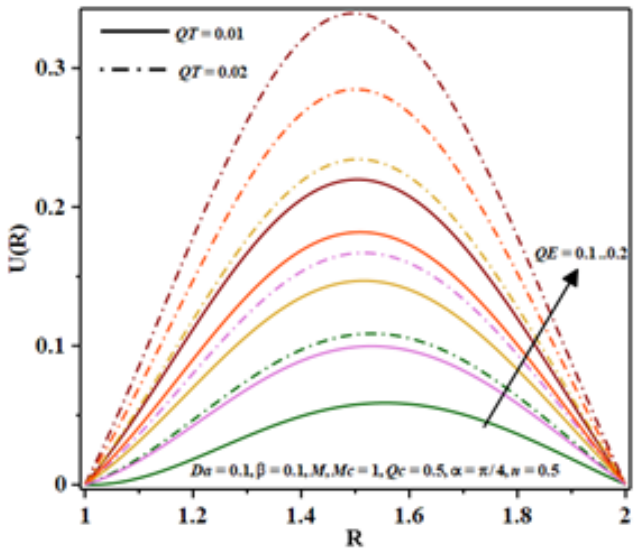


Figure 7. QT,QE's 's influence on Velocity profiles.

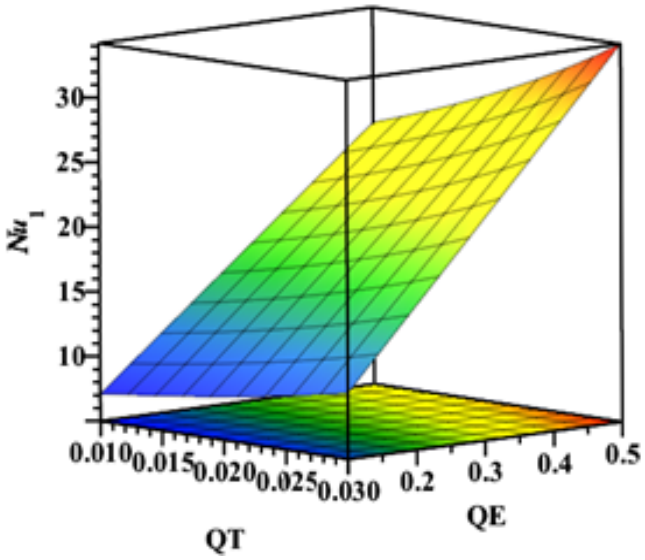


Figure 9. QT,QE's influence on Nu_1.

For 121 sets of 0.1≤QE≤0.5, 0.01≤QT≤0.03 values linear regression for Nu_1,τ_1, was performed (Table 3(a)).

Linear model for Nu_1 :

$$Nu_1 = \mathcal{K}_1 + \mathcal{K}_2 QE + \mathcal{K}_3 QT$$

Linear model for τ_1:

$$\tau_1 = \mathcal{K}_1 + \mathcal{K}_2 QE + \mathcal{K}_3 QT$$

Since the adjusted R^2 for τ_1 model is less, we perform quadratic regression for the same set of values of QE,QT, in which excellent correlation can be observed (Table 3(b)).

Quadratic model for τ_1 :

$$\tau_1 = \mathcal{K}_1 + \mathcal{K}_2 QE + \mathcal{K}_3 QE^2 + \mathcal{K}_4\, QE\, QT + \mathcal{K}_5\, QT + \mathcal{K}_6 QT^2$$

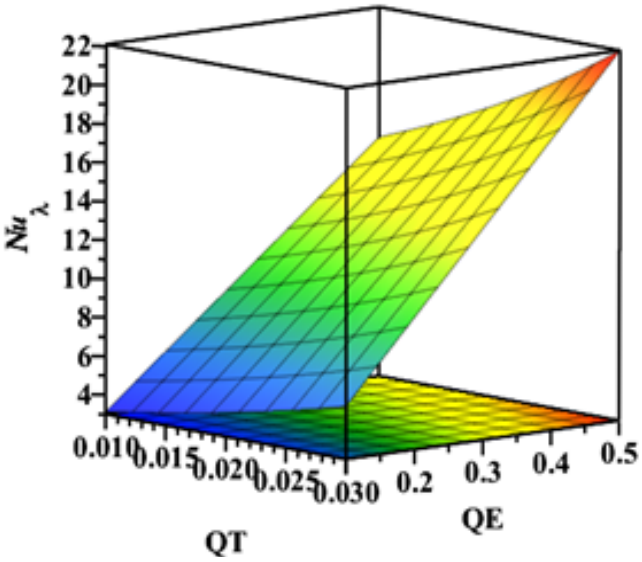


Figure 10. QT,QE's influence on Nu_λ

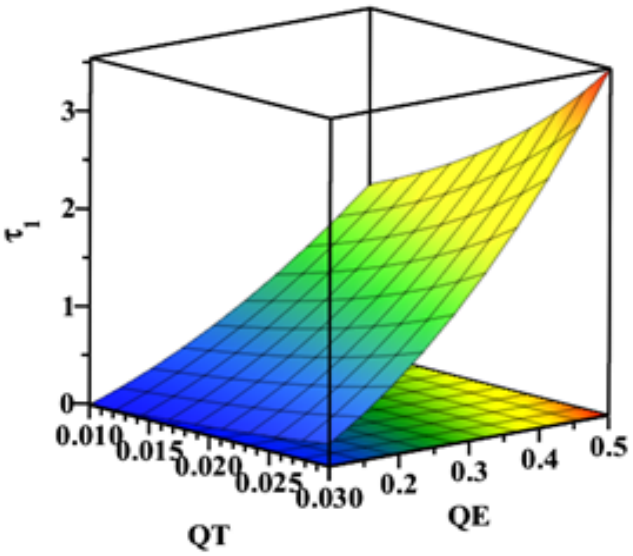


Figure 11. QT, QE's influence on τ_1.

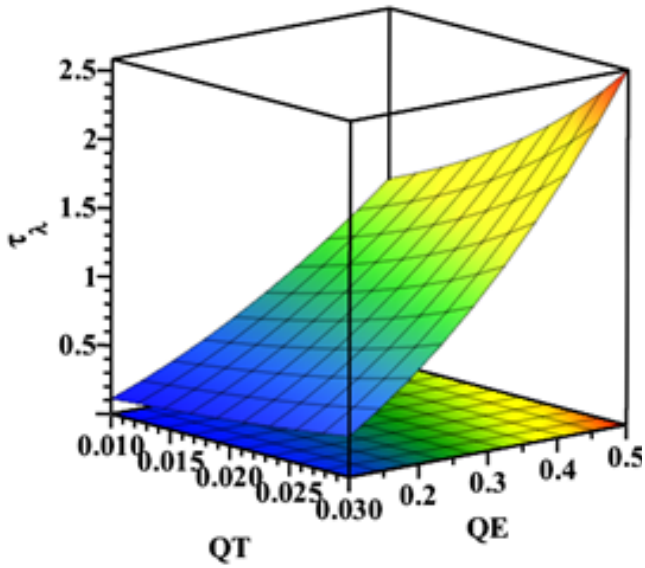


Figure 12. . QT,QE's influence on τ_λ.

Linear and quadratic regression for other key parameters were also performed to understand the statistical significance of the parameters (Table 3(c),(d)).

Linear model for τ_1:

$$\tau_1 = \mathcal{K}_1 + \mathcal{K}_2\alpha + \mathcal{K}_3\beta + \mathcal{K}_4 QC + \mathcal{K}_5 Da$$

Quadratic model for τ_1:

$$\tau_1 = \mathcal{K}_1 + \mathcal{K}_2\alpha + \mathcal{K}_3\beta + \mathcal{K}_4 QC + \mathcal{K}_5 Da + \mathcal{K}_6\alpha\beta + \mathcal{K}_7\alpha QC + \mathcal{K}_8\alpha Da + \mathcal{K}_9\beta QC + \mathcal{K}_{10}\beta Da + \mathcal{K}_{11} QC\, Da + \mathcal{K}_{12}\alpha^2 + \mathcal{K}_{13}\beta^2 + \mathcal{K}_{14} QC^2 + \mathcal{K}_{15} Da^2$$

It is clear that quadratic polynomial for τ_1 has more correlation with the parameters except QC. QC has less p-value greater than usual significance level of 0.05. Hence QC is not statistically significant for the model. Further the parameters α,β,Da have negative corelation

Table 3(a). Linear Regression Model for Nu_1 and Nu_λ

Coefficients	K_1	K_2	K_3	Adjusted
Nu_1	-129.6530	178.6658	11682.123	0.9893
-value	0	0	0	
τ_1	-18.2180	29.1897	1460.0128	0.9347
-value	0	0	0	

Table 3(b). Quadratic Regression Model for τ_1

Coefficients	τ_1	p-value
K_1	65.6116	0
K_2	-361.0278	0
K_3	408.3049	0
K_4	26526.501	0
K_5	- 9546.0105	0
K_6	355014.20	0
Adjusted R^2	0.9976	

Table 3(c). Linear Regression Model for τ_1 with α,β,QC,Da as dependent variable

Coefficients	τ_1	p-value
K_1	-6.7951	0
K_2	-2.8763	0
K_3	2.1358	0
K_4	6.2912	0
K_5	8.8027	0
Adjusted R^2	0.93221	

with the skin friction coefficient and QC shows the positive correlation.

Table 3(d). Quadratic Regression Model for τ_1 with α,β,QC,Da as dependent variable

Coefficients	τ_1	p-value
K_1	-1.7097	0.0196
K_2	30.5027	0
K_3	-15.9817	0.0003
K_4	-1.8451	0.1972
K_5	-8.4096	0
K_6	-12.7664	0
K_7	-23.9764	0
K_8	-49.8033	0
K_9	17.2812	0
K_{10}	7.56214	0
K_{11}	68.3873	0
K_{12}	-52.0576	0
K_{13}	-2.4850	0
K_{14}	3.1042×10^{-7}	0.9999
K_{15}	-214.1241	0
Adjusted	0.9951	

5.0 Conclusions

The influence of viscosity which depends on temperature on the flow of nanofluid with kinematics of nanoparticle aggregation in a porous annulus region with an inclination is studied. The analysis encompasses the NBA and the heat transport phenomenon featuring ESHS, and THS. Some of the major outcomes of the study are given below:

- The momentum of the nanofluid with aggregation of the nanoparticles is less dominated by the increase in the angle of inclination.
- The velocity field is favoured by the temperature-dependent variable viscosity mechanism.
- The flow structure has an ascending nature in the porous region when Da≠0.
- The momentum of the considered flow benefits from both quadratic convection and mixed convection mechanisms, in addition to the presence of the ESHS and THS phenomena.
- Friction factor and heat transport are more when QE,QT are high.
- α, β, Da has negative correlation and QC has positive correlation with the skin friction.

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