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ORIGINAL ARTICLE

Stefan blowing effect on bioconvective flow of nanofluid over a solid rotating stretchable disk

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Abstract A mathematical model for the unsteady forced convection over rotating stretchable disk in nanofluid containing micro-organisms and taking into account Stefan blowing effect is presented theoretically and numerically. Appropriate transformations are used to transform the governing boundary layer equations into non-linear ordinary differential equations, before being solved numerically using the Runge-Kutta-Fehlberg method. The effect of the governing parameters on the dimensionless velocities, temperature, nanoparticle volume fraction (concentration), density of motile microorganisms as well as on the local skin friction, local Nusselt, Sherwood number and motile microorganisms numbers are thoroughly examined via graphs. It is observed that the Stefan blowing increases the local skin friction and reduces the heat transfer, mass transfer and microorganism transfer rates. The numerical results are in good agreement with those obtained from previous literature. Physical quantities results from this investigation show that the effects of higher disk stretching strength and suction case provides a good medium to enhance the heat, mass and microorganisms transfer compared to blowing case.

1. Introduction

Rotating flows have applications in many industries and natural phenomena. Studies on rotating disk problem rely on the solution to the governing equations. Von Kármán [1] was the first to study steady flow over a solid rotating disk by an integral method [2]. Cochran and Goldstein [3] improved Von Kármán [1] solution by using patching two series solution. Accordingly, model was improved by Benton [4] who extended the hydrodynamic problem to flow starting impulsively from rest. A study by Bodonyi [5] has found the unsteadiness in rotating disk problem is caused by impulsively rotating disk. Pop [6] studied two-dimensional unsteady flow due to eccentric disk rotation for

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Nomenclature

$\tilde{b}$	chemotaxis constant (unit: dimensionless)
$\overline{C}$	nanoparticles volume fraction (unit: dimensionless)
$\overline{C}_f$	fluid nanoparticles volume fraction (unit: dimensionless)
$\overline{C}_{f\overline{r}}$	local skin friction coefficient in $\overline{r}$-direction
$\overline{C}_{f\theta}$	local skin friction coefficient in θ-direction
$\overline{C}_w$	wall nanoparticles volume fraction (unit: dimensionless)
$\overline{C}_\infty$	ambient nanoparticle volume fraction (unit: dimensionless)
D_B	Brownian diffusion coefficient (unit: m^2/s)
D_n	microorganism diffusion coefficient (unit: m^2/s)
D_T	thermophoretic diffusion coefficient (unit: m^2/s)
$f(\eta)$	dimensionless axial stream function (unit: dimensionless)
fw	Stefan blowing parameter $\left(fw = \left(\overline{C}_f - \overline{C}_\infty\right)/2(1-\overline{C}_w)\right)$
$g(\eta)$	dimensionless circumferential stream function (unit: dimensionless)
h_m	mass transfer coefficient
Le	Lewis number $\left(Le = \alpha/D_B\right)$
Lb	bioconvection Schmidt number $\left(Lb = \alpha/D_m\right)$
m_w	surface mass flux (unit: W/m^2)
Nb	Brownian motion parameter $\left(Nb = \tau D_B \Delta C/\alpha\right)$ (unit: dimensionless)
Nd	Biot number $\left(Nd = \left(h_m/D_B\right)\left(\sqrt{\left(\nu(1-\beta\overline{t})/\Omega\right)}\right)\right)$ (unit: dimensionless)
Nt	thermophoresis parameter $\left(Nt = \tau D_T \Delta T/T_\infty \alpha\right)$ (unit: dimensionless)
$Nu_{\overline{r}}$	local Nusselt number $\left(Nu_{\overline{r}} = \overline{r} q_w/k_f(\overline{T}_w - \overline{T}_\infty)\right)$ (unit: dimensionless)
$\overline{n}$	number of motile microorganism (unit: dimensionless)
$\overline{n}_w$	wall motile microorganisms (unit: dimensionless)
$\overline{P}$	fluid pressure
Pe	bioconvection Péclet number $\left(Pe = \tilde{b} W_c/\nu\right)$ (unit: dimensionless)
Pr	Prandtl number $\left(Pr = \nu/\alpha\right)$ (unit: dimensionless
q_n	surface microorganism flux
q_w	surface heat flux (unit: W/m^2)
$Q_{n\overline{r}}$	local wall motile microorganism number $\left(Q_{n\overline{r}} = \overline{r} q_n/D_n \overline{n}_w\right)$
$\overline{r}$	dimensional coordinate along the plate (unit: m)
$Re_{\overline{r}}$	local Reynolds number $\left(Re_{\overline{r}} = \Omega\, \overline{r}^2/\nu\right)$
S	unsteadiness parameter $\left(S = \beta/\Omega\right)$
$Sh_{\overline{r}}$	local Sherwood number $\left(Sh_{\overline{r}} = \overline{r} m_w/D_B(\overline{C}_w - \overline{C}_\infty)\right)$
$\overline{t}$	time (unit: s)
$\overline{T}$	nanofluid temperature (unit: K)
$\overline{T}_f$	fluid temperature (unit: K)
$\overline{T}_w$	wall temperature (unit: K)
$\overline{T}_\infty$	ambient temperature (unit: K)
$\overline{u}_{\overline{r}}$	velocity components along the $\overline{r}$-axis (unit: m/s)
$\overline{u}_{\overline{z}}$	velocity components along the $\overline{z}$-axis (unit: m/s)
$\overline{u}_\theta$	velocity components along the θ-axis (unit: m/s)
W_c	maximum cell swimming speed (unit: m/s)
$\overline{z}$	dimensional coordinate normal to the plate (unit: m)

Greek letters

α	effective thermal diffusivity (unit: m^2/s)
α_c	disk stretching parameter (unit: dimensionless)
β	constant (unit: dimensionless)
$\chi(\eta)$	dimensionless number of motile microorganism (unit: dimensionless)
$\phi(\eta)$	dimensionless nanoparticles volume fraction (unit: dimensionless)
η	independent similarity variable (unit: dimensionless)
μ	dynamic viscosity of the fluid (unit: kg/(m $\cdot$ s))
$\theta(\eta)$	dimensionless temperature (unit: dimensionless)
ρ_f	nanofluid density (unit: kg/m^3)
τ	ratio of the effective heat capacity of the nanoparticle material to the fluid heat capacity (unit: dimensionless)
$\tau_{\overline{r}}$	skin friction in $\overline{r}$-direction (unit: Pa)
τ_θ	skin friction in θ-direction (unit: Pa)
ν	kinematic viscosity (unit: m^2/s)
ψ	stream function (unit: m^2/s)

which both the disk and fluid are at rest. Erdogan [7] next extended Pop [6] and suggested three-dimensional problem which considered the problem involving both disk and fluid at rest. He proposed that both the disk and fluid at infinity are initially rotating about z-axis with the same angular velocity. Recently, a series of studies rely on rotating disk was investigated by Turkyilmazoglu [8,9] and [10]. Turkyilmazoglu [8] and [9] first focuses on the three dimensional steady flow of an electrically conducting fluid over a rotating stretchable disk with a uniform magnetic field. Next, Turkyilmazoglu [10] extended his previous researches by using water-based nanofluids into the model. Asghar et al. [11] used the Lie group analysis to study three dimensional of viscous fluid on a stretchable rotating disk in radial direction. Sheikholeslami [12] investigated MHD flow and heat transfer with the combined effects of different types of nanofluids and injection/suction parameter between two parallel plates in a rotating system. Srinivas et al. [13] applied the method of HAM to study the unsteady MHD viscous fluid flow between expanding/contracting rotating porous disks with viscous dissipation. They found that the percentage to increase in dimensionless temperature is much higher for the combined effect of expansion disk with injection compared to contraction disk with injection. Dandapat et al. [14] studied uniform transverse magnetic field on unsteady two-layer film flow over a rotating disk under planar interface assumption. Sheikholeslami et al. [15] considered the three dimensional steady flow of condensation film on inclined rotating disk to study the effect of nanofluid spraying for cooling process. Studies on three-dimensional unsteady rotating disk include those of Hobiny et al. [16], Watson and Wang [17], Rashidi et al. al [18], Sparrow and Cess [19] and Khan et al. [20].

Interest in the use of nanofluids to enhance the flow, heat and mass transfer has developed significantly among many researchers. The term ‘nanofluids’ was first suggested by Choi [21] to describe the pure fluids with suspended nanoparticles. He defined nanofluid as a fluid containing