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NUMERICAL STUDY OF MAGNETIC-BIO-NANO-POLYMER SOLAR CELL COATING MANUFACTURING FLOW

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ABSTRACT

Novel **bio-nano-electro-conductive polymers** are currently being considered for third generation organic solar coatings which combine biological micro-organisms, nanofluids and magnetic polymer properties. Motivated by these developments, in this poster, we describe a mathematical model for simulating the manufacturing fluid dynamics of such materials. Incompressible, steady-state, boundary layer magneto-bioconvection of a nanofluid (containing motile gyrotactic micro-organisms) over a nonlinear inclined stretching sheet subjected to non-uniform magnetic field is studied theoretically and numerically. Buongiorno's two-component nanofluid model (developed at MIT) is deployed with the Oberbeck-Boussinesq approximation. Ohmic dissipation (Joule heating) is included. The governing nonlinear partial differential equations are reduced to a system of ordinary differential equations with appropriate similarity transformations. The normalized system of equations with associated boundary conditions feature a number of important dimensionless parameters including magnetohydrodynamic body force parameter (M), sheet inclination (δ), Brownian motion nanoscale parameter (Nb), thermophoresis nanoscale parameter (Nt), Richardson number (Ri=Gr/Re^2, where Gr is thermal Grashof number and Re is Reynolds number), buoyancy ratio parameter (Nr), Eckert (viscous dissipation) number (Ec), bioconvection Rayleigh number (Rb), Lewis number (Le), bioconvection Lewis number (Lb), Péclet number (Pe), nonlinear stretching parameter (n) are solved with a variational Finite Element Method (**FEM**). Validation is conducted with earlier published studies for the case of non-magnetic stretching sheet nanofluid flow without bioconvection. The response of non-dimensional velocity, temperature, nanoparticle concentration, motile micro-organism density function, local skin friction coefficient, Nusselt number, Sherwood number, wall motile density gradient with variation in physically pertinent values of selected control parameters (representative of real solar bio-nano-magnetic materials manufacturing systems) are studied in detail. Interesting features of the flow dynamics are elaborated of relevance to the performance of bio-magneto-nano polymeric solar coatings.

INTRODUCTION

Among the most promising developments in solar coatings is ***organic solar paint***. This environmentally-friendly technology takes the form of coatings or flexible polymeric sheets that are precision-designed to contain a nano-particle fluid that is essentially water-based paint. The presence of the nano-particles has been confirmed to enhance durability, anti-corrosion and anti-abrasion characteristics of solar coatings which may be regarded as smart thermochromic materials [1, 2]. These materials may also be electrically-conducting i.e. magnetized. In this case *electro-conductive polymeric solar materials* (e.g. magnetized sol gels) can lead to a more consistent and predictable power output and sustained efficiency. Solar gel coated systems constitute third generation solar designs (organic polymer-based nano-coatings) which are superceding the earlier first generation (silicon-based) and second generation (thin film) solar cells. The parallel developments in biomimetics and exploiting biological phenomena for technological designs has also led to interest in embedding micro-organisms in certain coatings. Bacterial micro-organisms have tremendous anti-fouling properties and also protect engineering surfaces from environmental contamination. The resulting materials are sometimes called **biofunctional materials** [3]. Functional surfaces with UV or visible light–active photocatalyst content can circumvent environmental degradation due to photocatalytic properties. Due to these properties, a wide range of pathogen bacteria can be inactivated under visible light illumination. When nano-doping, magnetic properties and embedded micro-organisms are combined a new generation of solar coatings is achieved, namely *magneto-nano-bio-coatings* [4]. **The fundamental basis for nano-coatings (whether magnetic or biologically modified) is *nanofluid science and technology*.** Here we study the r gyrotactic bioconvection nanofluid magnetized boundary layer flow from an *inclined* non-linear stretching surface *in the presence of significant viscous dissipation and Ohmic dissipation (Joule heating).* The inclination of the fabrication surface permits the scaling of gravity effects which provide a further mechanism of controlling the magnetic bio-nano-materials processing operations.

MATHEMATICAL MODEL

Two-dimensional, steady, laminar, incompressible, viscous boundary layer flow of electrically-conducting nanofluid containing gyrotactic micro-organisms from a nonlinear stretching sheet which is inclined from the vertical with an acute angle δ is considered. The physical model is shown in **Fig 1**. The x-direction is taken along the leading edge of the inclined stretching sheet and the y-direction is normal to it. Water is considered as base fluid and this allows the proliferation of thermophile gyrotactic micro-organisms. The sheet (magneto-bio-nano-solar coating) is stretched with a power-law velocity i.e. stretching velocity $u_w = ax^n$ where a is a positive constant and n is termed the *nonlinear stretching parameter*. A variable intensity magnetic field $B(x) = B_o x^{(n-1)/2}$ is applied in the direction parallel to the y-axis. Joule heating (Ohmic dissipation) is included. However induced magnetic is negligible compared to external magnetic field. The nanofluid suspension is dilute since there is no agglomeration and accumulation of nanoparticles i.e. homogenous dispersion is achieved. Additionally, implicit to the model is the assumption that nanoparticles have no effect on the direction and velocity of gyrotactic micro-organisms swimming. Buongiorno's MIT nanoscale model [5] is used.

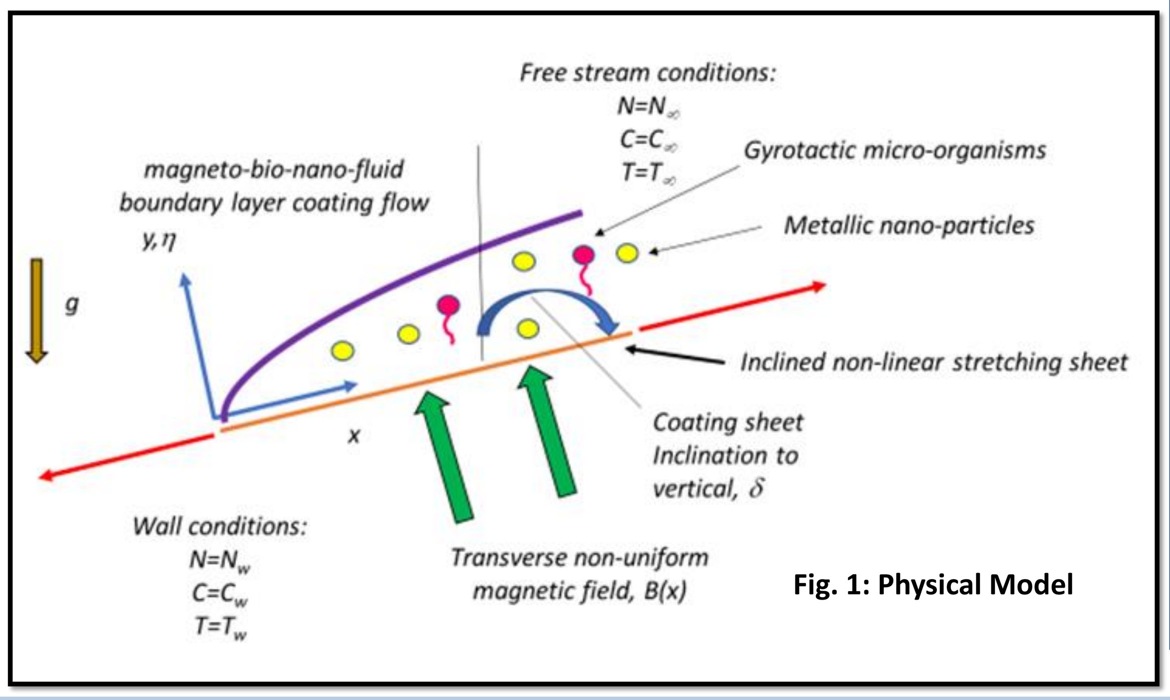

Fig. 1: Physical Model

MATHEMATICAL MODEL

The governing conservation equations for mass, momentum, energy (heat), nano-particle species concentration and motile micro-organism density conservation with associated boundary conditions are:

Mass:

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

x- Momentum:

$$\rho f\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial x}+u_f\left(\frac{\partial^2 u}{\partial x}+\frac{\partial^2 u}{\partial y^2}\right)+\rho_f g\beta(1-C_\infty)(T-T_\infty)cos\delta-g(\rho_p-\rho_f)(C-C_\infty)cos\delta-gy(\rho_m-\rho_f)(N-N_\infty)cos\delta-\sigma B^2(x)u$$

y- Momentum:

$$\frac{\partial P}{\partial y}=0$$

Energy (Heat)

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\tau\left\{D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right)\right\}+\frac{\mu\alpha}{k}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma\alpha B^2(x)u^2}{k}$$

Nano-particle species

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\alpha\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial x^2}\frac{\partial^2 T}{\partial y^2}\right)$$

Gyrotactic micro-organism conservation:

$$u\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}+\frac{bW_c}{(C_w-C_\infty)}\left[\frac{\partial}{\partial x}\left(N\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(N\frac{\partial C}{\partial y}\right)\right]=D_m\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial y^2}+2\frac{\partial^2 N}{\partial xy}\right)$$

Wall boundary conditions:

$$=ax^2,\quad v=0,\quad T=T_w,\quad C=C_{w,}\quad N=N_w\quad at\ x=0$$

Wall boundary conditions:

$$u\to 0,\quad v\to 0,\quad T\to T_\infty,\quad C\to C_\infty,\quad N\to N_\infty\quad at\ x\to\infty$$

Introduce similarity transformations

$$n=y\sqrt{\frac{a(n+1)}{2y}}x^{\frac{(n-1)}{2}},\quad u=ax^n f'(n),\quad v=-\sqrt{\frac{a(n+1)}{2y}}x^{\frac{(n-1)}{2}}\left(f(\eta)+\frac{(n-1)}{(n+1)}\eta f'(\eta)\right),\ \theta(\eta)=\left(\frac{T-T_\infty}{T_w-T_\infty}\right),\quad \emptyset(\eta)=\left(\frac{C-C_\infty}{C_w-C_\infty}\right),\quad x(\eta)=\frac{N-N_\infty}{N-N_\infty}$$

NON-DIMENSIONAL BOUNDARY VALUE PROBLEM (BVP)

$$f'''+ff''-\left(\frac{2n}{n+1}\right)(f')^2-Mf'+\left(\frac{2}{n+1}\right)\left(\frac{Gr}{Re^2}\right)(\theta cos\delta-Nrcos\delta-Rb\chi cos\delta)=0$$

$$\frac{1}{Pr}\theta''+\theta'(f+Nb\phi')+Nt(\theta')^2+Ec[(f'')^2+2M(f')^2]=0$$

$$\phi''+Lef\phi'+\left(\frac{Nt}{Nb}\right)\theta''=0$$

$$x''+Lbfx'-Pe[\phi''(\Omega+\chi)+\phi'x']=0$$

$$f'(\infty)=0,\quad \theta(\infty)=0,\quad \emptyset(\infty)=0,\quad \chi(\infty)=0$$

$$f(0)=0,\quad f'(0)=1,\quad \theta(0)=1,\quad \chi(0)=1,$$

$$Nb=\frac{\tau D_B(C_w-C_\infty)}{\alpha},\quad Nt=\frac{\tau D_B(T_w-T_\infty)}{\alpha T_\infty},\quad M=\frac{2\sigma B_o^2}{ap(n+1)},\quad \frac{Gr}{Re^2}=\frac{(g\beta(1-C_\infty)(T_w-T_\infty)x^3/v^2)}{u_w^2x^2/v^2},$$

$$Nr=\frac{(\rho_p-\rho_f)(C_w-C_\infty)}{\rho\beta(1-C_\infty)(T_w-T_\infty)},\quad Rb=\frac{\gamma(\rho_m-\rho_f)(N_w-N_\infty)}{\rho\beta(1-C_\infty)(T_w-T_\infty)},\quad Pr=\frac{\nu}{\alpha},\quad Le=\frac{\nu}{D_B},\quad Lb=\nu/D_m,$$

$$Ec=\frac{u_w^2}{c_p(T_w-T_\infty)},\quad Pe=\frac{bW_c}{D_m},\quad \Omega=\frac{N_\infty}{(N_w-N_\infty)}.$$

Here Nb is Brownian motion parameter, Nt is thermophoresis parameter, M is magnetic parameter, Gr/Re^2 is thermal buoyancy parameter, Nr is species to thermal buoyancy force ratio, Rb is bioconvection, Pr is Prandtl number, Le is Lewis number, Lb is bioconvection Lewis number, Ec is Eckert number, Pe is bioconvection Peclet number, Rayleigh *Ω is* motile micro-organisms concentration difference parameter.

FEM SOLUTION OF BVP AND VALIDATION

The nonlinear ordinary differential BVP which characterizes the solar magnetized bioconvection nanofluid coating regime is solved numerically by the variational finite element method. The whole finite element domain is divided into 80 two-node line elements, over each of the element, finite element equations are derived. The error tolerance has been considered to be 10^{-4}. The choice of $\eta_\infty = 7$ satisfies the "infinity" boundary conditions i.e. achieves asymptotically smooth results in the free stream. If η_∞ exceeds 7, all the unknown functions do not change up to the desired accuracy. Mesh independence test were also conducted. 80 elements were found to achieve good accuracy with further mesh refinement having no impact on the accuracy. Details are given in Bég [6]. For the validation of code, careful comparison with special cases of the general model is conducted. **Table 1** shows the benchmarking of the present finite element solutions for reduced Nusselt number with the earlier studies of Khan and Pop [7] for the case where bioconvection is ignored (*Rb = Pe. = Lb = Ω = N r = 0), the sheet is vertical (δ = 0°), linear sheet stretching velocity is assumed (n = 1), magnetic field and viscous heating and Joule dissipation terms vanish (M=Ec =0) but nano-particle effects are retained (Le =10) and Nb≠ 0 and Nt ≠ 0).* Excellent correlation is achieved between the variational finite element code and the numerical shooting quadrature computations of Khan and Pop [7] for all values of Brownian motion parameter (*Nb*) and thermophoresis parameter (*Nt*).

NUMERICAL RESULTS

Nt	Nb = 0.1		Nb = 0.3		Nb = 0.3	
	FEM	Khan and Pop [7]	FEM	Khan and Pop [7]	FEM	Khan and Pop [7]
0.1	0.956638	0.952493	0.256755	0.2522	0.05596	0.0543
0.2	0.69398	0.6932	0.181657	0.1816	0.0394372	0.0390
0.3	0.524139	0.5201	0.131437	0.1355	0.0299327	0.0291
0.4	0.408426	0.4026	0.100644	0.1046	0.0221499	0.0225
0.5	0.32752	0.3211	0.08291	0.0833	0.0175823	0.0179

Comparison of results for reduced Nusselt number $\sqrt{\frac{n+1}{2}}\theta'(0)$, for *Le = 10, n = 1, M =Ec = Nr = Rb = Pe = Lb = Ω = 0, δ = 0°* and different values for *Nt and Nb with Khan and Pop [7]*

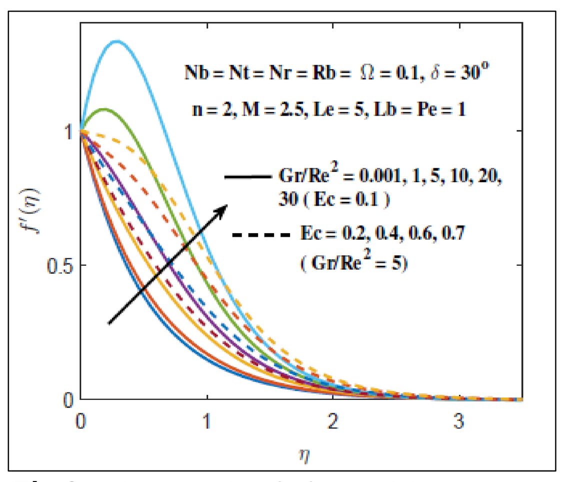

Fig 2: Eckert number (*Ec*) and Richardson number (*Ri = Gr/Re²*) effects on dimensionless velocity

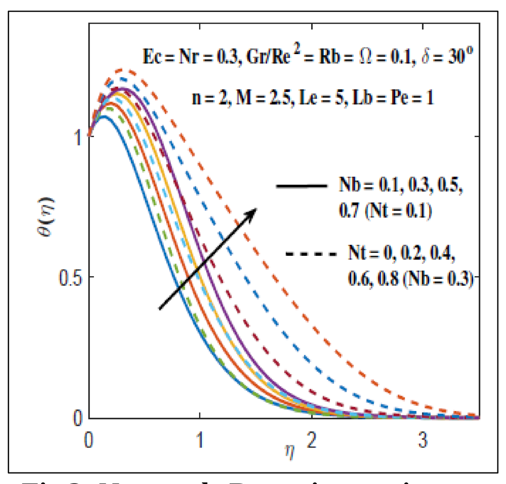

Fig 3: Nanoscale Brownian motion parameter (*Nb*) and thermophoresis parameter (*Nt*) effects on dimensionless temperature

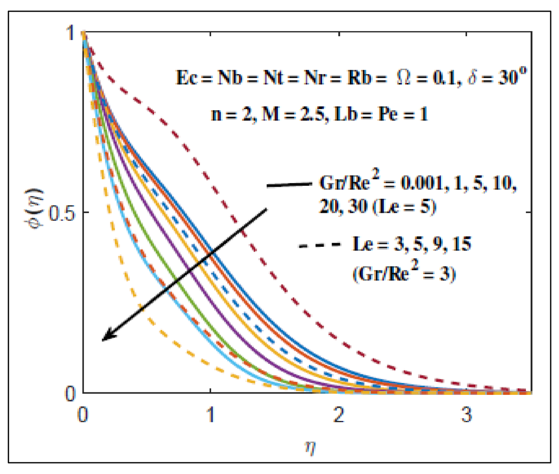

Fig 4: Effect of Richardson number (*Ri = Gr/Re²*) and Lewis number (*Le*) on dimensionless nano-particle concentration

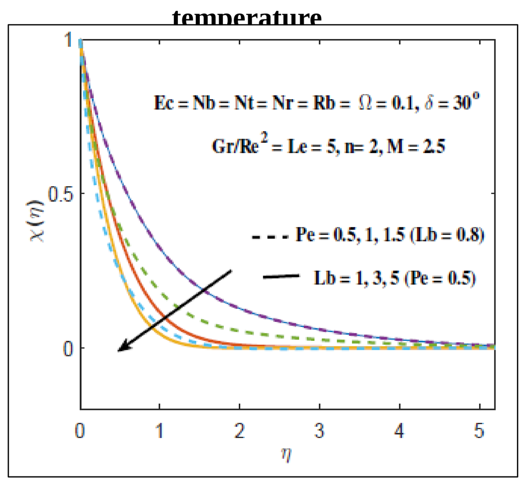

Fig 5: Effect of bioconvection Lewis number (*Le*) and bioconvection Péclet number (*Pe*) on *micro-organism density*

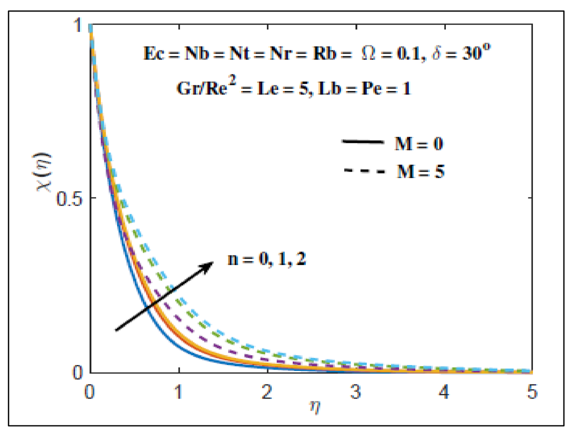

Fig 6: Effect of magnetic body force parameter (*M*) and nonlinear stretching parameter (*n*) on *motile micro-organism density number*

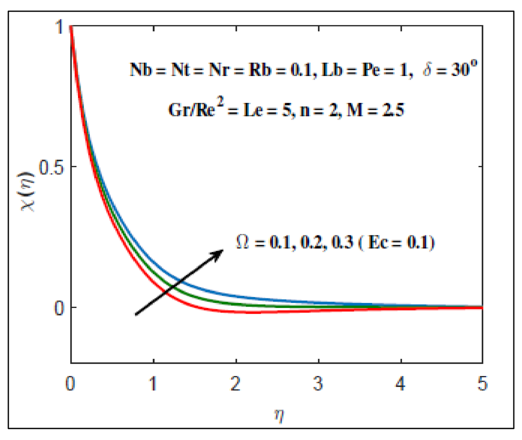

Figure 7: Effect of micro-organism concentration difference parameter (Ω) on *motile micro-organism density number*

Note- **Bioconvection Lewis number** *Le* relates the viscous diffusion rate (viscosity of fluid) to the motile micro-organism diffusivity. When this parameter is equal to unity both viscous diffusion and motile micro-organism diffusion rates are the same. **Bioconvection Péclet number *Pe*** increasing implies greater swimming speed i.e. micro-organisms propel faster and this *decreases their concentrations*. For *Pe>1*, swimming motions will dominate species diffusivity of micro-organisms and this will lead to a reduction in density of motile micro-organisms. The converse behaviour would arise for *Pe<1*. In the Buongiorno model the parameter *Nb* is inversely proportional to the size of nano-particles (which are assumed spherical and homogenously distributed in the base fluid). With greater *Nb* values smaller nano-particles are present and this intensifies the thermal conduction heat transfer from the particles to the surrounding fluid. This achieves the thermal enhancement which characterizes nanofluids and makes nano-particles promising in solar coatings [8].

CONCLUSIONS

Selected **FEM** computations for the impact of bioconvection, magnetic field, geometric (inclination), thermophysical (buoyancy) and nanoscale parameters on key flow characteristics in solar magneto-bio-nano coating manufacturing flow are shown in Figs 2-7. The main observations of the present study can be summarized as follows:

1)Velocity is decreased (and momentum boundary layer thickness increased) with increasing angle of inclination of the stretching sheet, Richardson number, Eckert number, buoyancy ratio parameter and bioconvection Rayleigh number.
2) Temperature is enhanced (and thermal boundary layer thickness elevated) with increasing angle of inclination, Richardson number, Eckert number, Brownian motion parameter, thermophoresis parameter and buoyancy ratio parameter.
3) Nano-particle concentration (volume fraction) is boosted (and nano-particle concentration boundary layer thickness is also enhanced) with increasing angle of inclination and thermophoresis parameter whereas it is depressed with Richardson number, Lewis number and Brownian motion parameter.
4) Motile micro-organism density number (and therefore also motile micro-organism species boundary layer thickness) is increased with enhancement in angle of inclination, magnetic parameter and nonlinear stretching parameter whereas it is suppressed with increasing bioconvection Lewis number, bioconvection Péclet number and Richardson number.
5) Local skin friction is increased with greater thermophoresis parameter and buoyancy ratio parameter.
6) Reduced Nusselt number (wall heat transfer rate) is reduced whereas Sherwood number (nano-particle wall species gradient) is enhanced with an increase in Brownian motion and thermophoresis parameters.
7) Motile micro-organism wall density gradient is elevated with an increase in both micro-organism concentration difference parameter and bioconvection Péclet number.

The present study has ignored thermal radiative heat transfer effects which are also important in high-temperature solar engineering and solar nano-materials processing. These will be considered in the future [9].

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