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An investigation on peristaltic flow of nanofluids: Application in drug conveyance frameworks

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ABSTRACT:*This paper studies the peristaltic flow of nanofluids through a two-dimensional channel. The analysis is conducted based on the long wavelength and low Reynolds number approximations. The walls of the channel surface propagate sinusoidally along the channel. The Buongiornio formulation for nanofluidsis employed. Approximate analytical solutions for nanoparticle fraction field, temperature field, axial velocity, volume flow rate, pressure gradient and stream function are obtained. The impact of the pertinent physical parameters i.e. thermal Grashof number, basic-density Grashof number, Brownian motion parameter and thermophoresis parameter on nanoparticle fraction profile, temperature profile, velocity profile and trapping phenomenon are computed numerically. The results of this study demonstrate good correlation with the Newtonian results of Shapiro et al. (1969) [4], which is a special case (GrT = 0, GrF = 0)of the generalized model developed in this article. Applications of the study include peristaltic micro-pumps and novel drug delivery systems in pharmacological engineering.*

KEYWORDS:*Peristaltic flow, Nanofluids, Grashof numbers, Brownian motion, Thermophoresis, Peristaltic pumps, Pharmacology.*

I. INTRODUCTION

Peristaltic pumping is a form of fluid transport which isachieved via a progressive wave of contraction or expansion whichpropagates along the length of a distensible tube containing fluids.In general, this pumping takes place from a region of lower pres-sure to higher pressure. It is an inherent property of many of thesmooth muscle tubes such as the gastrointestinal tract, male reproductive tract, fallopian tube, bile duct, ureter and oesophagus. Theprinciple of peristaltic transport is also exploited in many industrial applications. These include sanitary fluid transport, transportof corrosive fluids, blood pumps in heart lung machines, novelpharmacological delivery systems etc. Since the experimentalwork of Latham [1], many investigations [2–4] dealing with peristaltic flow for different flow geometries and under various assumptions, have been presented by employing analytical,numerical and experimental approaches. Fung and Yih[2], whopresented a model on peristaltic pumping using a perturbationtechnique, associated reflux with net backward flow. Barton andRaynor[3] studied the peristaltic motion in a circular tube by usingthe long wavelength approximation for intestinal flow. Shapiroet al. [4] extended their work for the steady flow of Newtonian flu-ids through the channel and tube with sinusoidal wall propagationand theoretically evaluated the reflux and trapping phenomena. The fluids present in the ducts of a living body can be classifiedas Newtonian and non-Newtonian fluids based on their shear-stressstrain behavior. Peristaltic transport on a microfluid scale has alsoreceived attention. Important studies of micro-peristaltic pumpsinclude Quake and Scherer [5]who have reported pneumaticvalves constructed in multilayer polydimethylsiloxane (PDMS) de-vices. These PDMS valves comprise overlapped fluidic and controlchannels (that reside in different layers) which are separated bya thin polymeric membrane. Increased pressure in the controlchannel results in the deformation of the PDMS membrane andclosing of the fluidic channel. Simple valves and peristaltic pumpsproduced by a series of valves have been demonstrated using thistechnology. Chou et al. [6] have described micro-peristaltic pumpswhich comprise two PDMS layers that are permanently bonded together. Fluidic channels that are 100 lm wide and 10 lm height(measured in the center of the channel) are formed within a thinfilm (30 lm) of PDMS. Control lines (200 lm wide) are moldedin a thick layer (

5000 lm) of PDMS and positioned above the fluidic channels. A thin membrane of polymer delineates the fluidicand control channels and permits the actuation of peristalticpumps and valves. Mathematical simulations of such devices aretherefore of great industrial importance.In numerous peristaltic pumps, heat transfer also plays animportant role and is strongly influenced by peristaltic flow fields.The influence of heat transfer on peristaltic flow of Newtonian andnon-Newtonian fluids has been reported for various geometricalconfigurations by for example, Vajravelu et al. [7] who considereda vertical porous annulus. Kothandapani and Srinivas[8] examinedhydromagnetic heat transfer in peristaltic flow in a porous medium. Mekheimer and Abdelmaboud [9] simulated the magneto-convective peristaltic flow in a vertical annulus. Hayat et al. [10]studied peristaltic magneto-convection in a porous medium channel. Akbar and Nadeem[11]derived solutions for viscoelasticchemically-reacting peristaltic flow and heat transfer in a stenoticvessel. Further studies include the recent investigations by Tripathi[12,13] and Tripathi et al. [14,15]for the dynamics of swallowingwith thermal transport effects. Transient peristaltic flows have alsobeen considered by Pandey and Tripathi[16–18] for a diverse spectrum of non-Newtonian fluids. Peristaltic flow of viscoelastic fluidswith different fractional models have additionally also receivedsome attention, as elaborated in [19–23].In recent years a new branch of fluid mechanics has emerged,namely nanofluid dynamics, which finds diverse applications inmedical science, energetics, biology and process systems engineering. Initial developments were made by Choi [24] in the realm ofenergy performance enhancement. Nanofluids as elucidated byXuan and Li [25] are a new class of fluids that are engineered bysuspending nanoparticles (NP) in ‘‘base’’ heat transfer fluids.Nanofluids are synthesized by dispersing the nano particles(NP) (nanometer-sized particles i.e. <100 nm) in the base fluid suchas water (H2O), ethylene–glycol (EG), or propylene–glycol (PG), cool-ants, biofluids, emulsions, oil, lubricants and silk fibroin (SF). A crea-tive combination of nanoparticles and liquid molecules are shown in Fig. 1. Although the concept of nanofluids was first pro-posed by the great Scottish theoretical physicist, James Clerk Maw-well in the late 19th century, more than a century later the term‘‘nanofluid’’ was officially introduced by the energy scientist Choi[24] who fabricated such nanofluids at the Argonne National Lab-oratory, Energy Technology Division based in Illinois, USA. Choi,in 1995 [24] pioneered the development of such fluids containingsuspensions of nanometer-sized particles and disclosed their significant thermal properties through the measurement of theconvective heat transfer coefficient of those fluids. Various benefitsof the application of nanofluids, such as improved heat transfer,size reduction of the heat transfer system, minimal clogging,microchannel cooling, and miniaturization of systems, wereachieved in his study. Since then investigations have been continued and recent potential identified in the biomedical device andpharmacological industries. Both convection and conduction heattransfer modes have been addressed in detail. Xuan and Li [25]measured convective heat transfer coefficients for Cu/water nano-fluids, and found substantial heat transfer enhancement. Lee et al.[26], measured conductive heat transfer coefficients of Al2O3/water, Al2O3/ethylene–glycol, CuO/water, and CuO/ethylene–gly-col nanofluids. Pak and Cho[27] investigated convective heattransfer in the turbulent flow regime using Al2O3/water and TiO2/water nanofluids, and observed that the Nusselt number of thenanofluids increased with increasing volume fraction of the suspended nanoparticles, and also with increasing Reynolds number.Lee and Choi [28] studied convective heat transfer of laminar flowsof an unspecified nanofluid in microchannels. Nanofluids were alsoobserved to have the ability todissipate heat power three timesmore effectively than pure water. Bég et al. [29] simulated numerically the unsteady magnetized nanofluid polymeric synthesis froma stretching sheet using Maple software, identifying the stronginfluence of time on nano-particle distributions. Zienali et al. investigated the convective heat transfer of Al2O3/water andCuO/water-based nanofluids in circular tubes, and observed that the heat transfer coefficient was enhanced by increasing the con-centration of nanoparticles in the nanofluids. Bég et al. [31]utilized a homotopy semi-computational algorithm to evaluate the thermaland nano-particle concentration boundary layer growth in the low-er stagnation-point regime of a sphere embedded in porous media.Maiga et al.[32] studied numerically the heat transfer enhance-ment in turbulent tube flow using Al2O3nanoparticles suspension.Buongiorno[33] presented a seminal analysis of convective trans-port in nanofluids using non-dimensionalization; this study haslaid the foundations for numerous subsequent analytical and numerical investigations including Kuznetsov and Nield [34,35],Kolade et al. [36], Kakaç and Pramuanjaroenkij [37] and Bachoket al. [38]. More complex nanofluid transport processes have beenconsidered by Uddin et al. [39]who employed Lie group algebraand numerical methods to compute the influence of nanofluidrhe-ology on thermofluid and mass transfer characteristics in heat-generating boundary layer flows. Bég et al. [40] simulated via aChebyshev spectral collocation scheme, the electrohydrodynamicpropulsion of nanofluids in drug delivery, evaluating the effectsof electrical Hartmann number and electrical Reynolds number. Adetailed review of progress in numerical simulation of nanofluiddynamic flows in biomechanics (renal and transdermal transport)has been presented very recently by Bég et al. [41], who have also employed single and two-phase particulate models and finite volume algorithms to evaluate the three-dimensional transportbehavior in bio-nano-polymer drug flows. Very few studies of peristaltic transport of nanofluids are available however in the literature, despite important applications in medical engineering systems. We quote here the very recent study by Akbar et al.[42]who studied peristaltic flow of a nanofluid in a diverging tube,coupling the temperature and nanoparticle equations using ahomotopy perturbation method. They showed that pressure risedecreases with the increase in thermophoresis number whereaselevating the Brownian motion parameter and the thermophoresisparameter induces a rise in temperatures the purpose of the present paper is to describe the influence ofnanoparticles on heat transfer and peristaltic flow through a two-dimensional channel. The problem is simplified by taking the lowReynolds number and long wavelength approximation. Solutions are benchmarked with the previous Newtonian, non-thermal studyof Shapiro et al. [4]. The effects of thermal Grashof number, basic-density Grashof number, Brownian motion parameter and thermophoresis parameter on nanoparticle fraction profile, temperature profile, velocity profile, and stream line distribution are discussedwith the aid of computational illustrations. This model is applicable to the simulation of particle flows in hemodynamic transportin small vessels and also nanofluid peristaltic pumps in biochemical and medical engineering. It is envisaged that the present study.

II. MATHEMATICAL MODEL

The constitutive equation for the wall geometry (cf. Fig. 2) duewhere qf; qp; l, g, b, (qc)f, (qc)p, k, T, F, DB, DTand qf0denote the fluid density, nanoparticle mass density, axial velocity,transverse velocity, transverse coordinate, pressure, fluid viscosity,acceleration due to gravity, volumetric expansion coefficient ofthe fluid, heat capacity of fluid, effective heat capacity of nanoparticle, thermal conductivity, temperature, nanoparticle volume fraction, Brownian diffusion coefficient, thermos phoretic diffusioncoefficient, and the nanofluid density at the reference temperature (T0). We then introduce the following non-dimensional parameters

III. NUMERICAL RESULTS AND DISCUSSION

The geometry of the peristaltic nanofluid regime is illustrated inFig. 2. In this section, the influence of pertinent nanofluid characteristics on the peristaltic flow pattern is studied graphically. Allillustrations have been generated with the Mathematica software.The effects of Brownian motion parameter (Nb) and thermophore-sis parameter (Nt) on nanoparticle fraction profile (U(g)) and temperature profile (h(g)) are presented through Figs. 3 and 4.The Brownian motion parameter, Nb, arises in the energy andspecies (nano-particle volume fraction) conservation equationsi.e. Eqs. (11) and (12), via the mixed derivative term, former, and the second order temperature derivative, in the latter. Clearly Nbis an important parameter therefore ininfluencing the species diffusion. Fig. 3(a) shows that with an in-crease in Brownian motion parameter (Nb), there is a strong de-crease in nanoparticle fraction profile U(g). The nanofluidbehaves more like a fluid than the conventional solid–fluid mixtures in which relatively larger particles with micrometer or millimeter orders are suspended. The nanofluid is a two-phase fluid innature and random movement of the suspended nanoparticles in-creases energy exchange rates in the fluid but depresses concentrations in the flow regime. We also note that with greater values ofdimensionless transverse coordinate,g, there is a pronounceddivergence in profiles i.e. as we migrate from the channel centerline(g = 0), the profiles move apart. This trend has also been observedby Akbar et al. [42]. Thermophoretic parameter (Nt) effects are depicted in Fig. 3(b). A marked elevation in U(g) values accompaniesan increase in Ntfrom 1 to 4. As with the Brownian motion parameter, Ntalso arise in both energy and nanoparticle volume concentration conservation equations (11) and (12), respectively.Although it features in the same term in the latter as Nb, in the former (Eq. (11)) it appears in a separate term, consistent with the ori-2ginal formulation of Buongiornio[33], viz. Hence speciesdiffusion is accentuated with thermophoresis. This pattern is alsoconsistent with macroscopic convection flows (non-nanofluid), asindicated by Zueco et al. [43]. Similar results have also been obtained in nanofluid studies by, for example Kuznetsov and Nield[34] among others, and more recently by Uddin et al. [39]usinga novel differential transform semi-numerical code. The positiveinfluence of Nton U(g) profiles is only apparent however forg> 1. Prior to this the effect is reversed and close to the longitudinal axis of the channel the nano-particle concentrations are infactdepressed with thermophoresis. This unusual response has alsobeen identified by Akbar and Nadeem[44], although actual elucidation requires experimental investigations. It indicate that both Nband Nt have a similar effect on temperature distributions in the flow regime for sometransverse distance from the channel centre, temperature h(g) isinitially enhanced with Brownian motion and with thermos phoresisi.e. the regime is heated. However for g > 1, the trends are reversed.As we approach the periphery of the channel, Brownian motionand thermophoresis tend to depress temperatures i.e. they act tocool the regime. Thermophoresis is the migration of nanoparticlesin the direction of a decreasing temperature gradient. Evidentlythis phenomenon has a potent effect on temperature evolutionthroughout the channel cross-section.Fig.5(a)–(e) show that axial velocity (u) is generally negative forthe channel half-space defined by 0 6 g 6 1; flow reversal i.e. back-flow is therefore taking place. Maximum velocities are always located at the channel centre, decaying smoothly to zero at theperiphery (channel wall).

Fig. 5(a) indicates that an increase inBrownian motion parameter, Nb, decreases magnitudes of the axialvelocity i.e. opposes backflow u-values therefore become more positive. The flow is therefore decelerated with Brownian motion. Asimilar response is computed for the effect of thermophoresisparameter in Fig. 5(b). Fig. 5(c) shows the effect of thermal Grashofnumber (GrT) on axial velocity distribution. This parametersignifies the relative influence of thermal buoyancy force andviscous hydrodynamic force. For GrT<

1, the peristaltic regime isdominated by viscous forces and vice versa for GrT> 1. For theintermediate case of GrT= 1 both thermal buoyancy and viscousforces are of the same order of magnitude, as described by Béget al. [45]. Velocity magnitudes are generally reduced with increasing thermal Grashof number. The profiles follow monotonicpatterns for 0.5 6 GrT6 1.5. However with GrT= 2, an undulatingprofile is observed from the channel centerline to the wall. Thermalbuoyancy generally serves to retard the flow in the regime.Fig. 5(d) reveals that the influence of the species (basic-density)Grashof number, GrF, is opposite to that of the thermal Grashofnumber. Increasing GrF, acts to increase magnitudes of the axialvelocity i.e. exacerbates the backflow in the regime. GrFrepresentsthe ratio of species buoyancy force to the viscous hydrodynamic

IV. CONCLUSIONS

The influence of nanofluid characteristics on peristaltic heattransfer in a two-dimensional axisymmetric channel have beenstudied analytically with the aid of Mathematica software. Thestudy has been motivated by applications in novel nanofluid drugdelivery systems in the digestive system. Numerical computationshave shown that:Increasing Brownian motion parameter (Nb), reduces nano-particle fraction profile U(g), whereas thermos phoreticparameter enhances (Nt) it.Temperature h(g) is initially enhanced with Brownianmotion and with thermophoresis i.e. the regime is heated.Increasing Brownian motion parameter, Nb, and thermophoretic parameter (Nt) suppress axial velocity (u) i.e. opposebackflow.Axial velocity (u) magnitudes are generally reduced withincreasing thermal Grashof number whereas the conversebehaviour is caused with increasing species Grashofnumber(GrF).Nanofluids tend to suppress backflow compared with Newtonian fluids.Increasing Brownian motion parameter (Nb) reduces pressure difference, whereas increasing thermophoretic parameter (Nt) strongly enhances pressure difference, for all valuesof averaged volume flow rate, Q .Increasing thermal and species (basic-density) Grashof numbers elevates pressure difference for all flow rates.The magnitude of trapped bolus is decreased with increasingthe magnitude of Grashof numbers.Decreasing Brownian motion parameter reduces the numberof boluses trapped.Decreasing thermophoretic parameter, causes the size ofboluses to be slightly increased i.e. reduces the reflux region.With decreasing thermal Grashof number bolus size isincreased.An increase in species Grashof number has a similar effect toreducing Brownian motion parameter i.e. the dual bolusstructure is reduced to a single bolus.The current study has examined a horizontal channel, neglecting gravitational effects. Future investigations will consider nano-fluid three-dimensional (3-D) peristaltic flows in an inclinedchannel and will be communicated imminently. Furthermore it ishoped that the present investigation will further stimulateresearchers interesting in conducting experiments on nanofluidperistaltic transport phenomena, which would provide a much-needed framework for validating mathematical models.

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