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A study on peristaltic flow of nanofluids: Application in drug delivery systems

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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 nanofluids is 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 ($Gr_T = 0$, $Gr_F = 0$) of the generalized model developed in this article. Applications of the study include peristaltic micro-pumps and novel drug delivery systems in pharmacological engineering.

1. Introduction

Peristaltic pumping is a form of fluid transport which is achieved via a progressive wave of contraction or expansion which propagates along the length of a distensible tube containing fluids. In general, this pumping takes place from a region of lower pressure to higher pressure. It is an inherent property of many of the smooth muscle tubes such as the gastrointestinal tract, male reproductive tract, fallopian tube, bile duct, ureter and oesophagus. The principle of peristaltic transport is also exploited in many industrial applications. These include sanitary fluid transport, transport of corrosive fluids, blood pumps in heart lung machines, novel pharmacological delivery systems etc. Since the experimental work 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], who presented a model on peristaltic pumping using a perturbation technique, associated reflux with net backward flow. Barton and Raynor [3] studied the peristaltic motion in a circular tube by using the long wavelength approximation for intestinal flow. Shapiro et al. [4] extended their work for the steady flow of Newtonian fluids through the channel and tube with sinusoidal wall propagation and theoretically evaluated the reflux and trapping phenomena. The fluids present in the ducts of a living body can be classified as *Newtonian* and *non-Newtonian* fluids based on their shear-stress strain behavior. Peristaltic transport on a microfluid scale has also received attention. Important studies of micro-peristaltic pumps include Quake and Scherer [5] who have reported pneumatic valves constructed in multilayer polydimethylsiloxane (PDMS) devices. These PDMS valves comprise overlapped fluidic and control channels (that reside in different layers) which are separated by a thin polymeric membrane. Increased pressure in the control channel results in the deformation of the PDMS membrane and closing of the fluidic channel. Simple valves and peristaltic pumps produced by a series of valves have been demonstrated using this technology. Chou et al. [6] have described micro-peristaltic pumps which comprise two PDMS layers that are permanently bonded together. Fluidic channels that are 100 μm wide and 10 μm height (measured in the center of the channel) are formed within a thin film (~30 μm) of PDMS. Control lines (200 μm wide) are molded in a thick layer (~5000 μm) of PDMS and positioned above the fluidic channels. A thin membrane of polymer delineates the fluidic and control channels and permits the actuation of peristaltic pumps and valves. Mathematical simulations of such devices are therefore of great industrial importance.

In numerous peristaltic pumps, heat transfer also plays an important role and is strongly influenced by peristaltic flow fields.

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Nomenclature

a	half width of the channel (m)
b	amplitude of the wave (m)
c	wave velocity (m/s)
D_B	Brownian diffusion coefficient (m^2/s)
D_T	thermophoretic diffusion coefficient (m^2/s)
F	nanoparticle volume fraction
g	acceleration due to gravity (m/s^2)
Gr_{F}	basic-density Grashof number
Gr_{T}	thermal Grashof number
$\tilde{h}$	transverse vibration of the wall (m)
k	thermal conductivity (W/m K)
N_b	Brownian motion parameter
N_t	thermophoresis parameter
$\tilde{p}$	pressure (N/m^2)
Pr	Prandtl number
q	volume flow rate (in wave frame) (m^3/s)
Q	volume flow rate (in laboratory frame) (m^3/s)
$\tilde{t}$	time (s)
T	temperature (K)
Re	Reynolds number
$\tilde{u}$	axial velocity (in laboratory frame) (m/s)
U	axial velocity (in wave frame) (m/s)
$\tilde{v}$	transverse velocity (in laboratory frame) (m/s)
V	transverse velocity (in wave frame) (m/s)

Greek symbols

β	volumetric expansion coefficient of the fluid
δ	wave number
λ	wavelength (m)
$\tilde{\xi}$	axial coordinate (m)
$\tilde{\eta}$	transverse coordinate (m)
ϕ	amplitude ratio
θ	dimensionless temperature
μ	fluid viscosity (N s/m^2)
$(\rho)_{\mathrm{p}}$	effective heat capacity of nanoparticle (J/K)
$(\rho c)_{\mathrm{f}}$	heat capacity of fluid (J/K)
ν	kinematic viscosity (m^2/s)
ρ_{p}	nanoparticle mass density (kg/m^3)
Φ	rescaled nanoparticle volume fraction
ψ	stream function (m^2/s)
ρ_{f}	fluid density (kg/m^3)
ρ_{f0}	fluid density at the reference temperature (T_0) (kg/m^3)
	The same symbols without (∼) represent the dimensionless form.

The influence of heat transfer on peristaltic flow of Newtonian and non-Newtonian fluids has been reported for various geometrical configurations by for example, Vajravelu et al. [7] who considered a vertical porous annulus. Kothandapani and Srinivas [8] examined hydromagnetic heat transfer in peristaltic flow in a porous medium. Mekheimer and Abd elmaboud [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 viscoelastic chemically-reacting peristaltic flow and heat transfer in a stenotic vessel. Further studies include the recent investigations by Tripathi [12,13] and Tripathi et al. [14,15] for the dynamics of swallowing with thermal transport effects. *Transient* peristaltic flows have also been considered by Pandey and Tripathi [16–18] for a diverse spectrum of non-Newtonian fluids. Peristaltic flow of viscoelastic fluids with different fractional models have additionally also received some attention, as elaborated in [19–23].

In recent years a new branch of fluid mechanics has emerged, namely *nanofluid dynamics*, which finds diverse applications in medical science, energetics, biology and process systems engineering. Initial developments were made by Choi [24] in the realm of energy performance enhancement. Nanofluids as elucidated by Xuan and Li [25] are a new class of fluids that are engineered by suspending 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 such as *water* (H_2O), *ethylene–glycol (EG), or propylene–glycol (PG), coolants, biofluids, emulsions, oil, lubricants and silk fibroin (SF)*. A creative combination of nanoparticles and liquid molecules are shown in Fig. 1. Although the concept of nanofluids was first proposed by the great Scottish theoretical physicist, James Clerk Mawwell 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 Laboratory, Energy Technology Division based in Illinois, USA. Choi, in 1995 [24] pioneered the development of such fluids containing suspensions of nanometer-sized particles and disclosed their significant thermal properties through the measurement of the convective heat transfer coefficient of those fluids. Various benefits of the application of nanofluids, such as improved heat transfer, size reduction of the heat transfer system, minimal clogging, microchannel cooling, and miniaturization of systems, were achieved in his study. Since then investigations have been continued and recent potential identified in the biomedical device and pharmacological industries. Both convection and conduction heat transfer modes have been addressed in detail. Xuan and Li [25] measured convective heat transfer coefficients for Cu/water nanofluids, and found substantial heat transfer enhancement. Lee et al. [26], measured conductive heat transfer coefficients of Al_2O_3/water, Al_2O_3/ethylene–glycol, CuO/water, and CuO/ethylene–glycol nanofluids. Pak and Cho [27] investigated convective heat transfer in the turbulent flow regime using Al_2O_3/water and TiO_2/water nanofluids, and observed that the Nusselt number of the nanofluids 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 flows of an unspecified nanofluid in microchannels. Nanofluids were also observed to have the ability to *dissipate* heat power *three times*

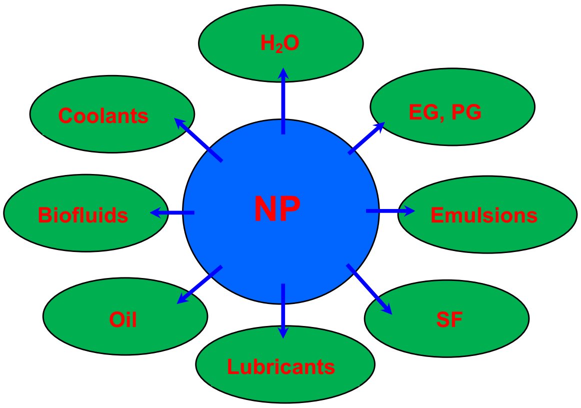

Fig. 1. Some possible combinations of nanoparticles and base fluids.