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Electro-Osmotically Driven Peristaltic Transport of Ellis Nano Fluid with Non-Fourier Heat Transfer in a Wavy Microchannel

Safeer Ahmed
The Department of Mathematics, Northern University, Nowshera, Pakistan
Email: safeerahmed.nu@gmail.com

Shakeela Andleeb
MPhil Scholar, Department of Mathematics, Northern University Nowshera

Asad Khan
MPhil Scholar, Department of Mathematics, Northern University Nowshera

ABSTRACT

This study presents an analytical investigation of Electro-Osmotically driven peristaltic transport of an Ellis Nano fluid in a symmetric wavy micro channel incorporating non-Fourier heat transfer effects. The Ellis rheological model is employed to characterize shear-thinning behaviour, while thermal transport is modelled using the Cattaneo–Christov heat flux formulation to account for thermal relaxation. Electro-osmotic forcing is incorporated through the linearized Poisson–Boltzmann equation under the low zeta potential approximation ($|\zeta| < 25$ mV).Using long-wavelength and low-Reynolds-number approximations, the governing nonlinear equations are reduced and solved analytically. The influence of the non-Newtonian parameter (β), electro-osmotic parameter (k), Helmholtz–Smoluchowski velocity (UHS), and Brinkman number (Br), and nanoparticle volume fraction (φ) on velocity, temperature, and trapping phenomena is quantified. Limiting-case validation demonstrates excellent agreement with previously published Newtonian and zero-electro-osmotic results. The model provides new insights into coupled electro-osmotic–non-Newtonian transport relevant to biomedical microfluidic systems and targeted drug delivery applications.

Keywords: Cattaneo–Christov Heat Flux; Ellis Fluid; Non-Newtonian Nano Fluid; Electro-Osmotic Flow; Heat and Mass Transfer; Linear Stability Analysis.

Introduction

Electro-osmotic transport in micro-scale systems has attracted significant attention due to its wide applications in biomedical engineering, microfluidic devices, lab-on-chip technologies, and targeted drug delivery systems. In micro channels containing ionic solutions, the interaction between electric double layer (EDL) and externally applied electric field generates bulk fluid motion, commonly described through the Poisson–Boltzmann formulation and Helmholtz–Smoluchowski velocity concept. The non-Newtonian fluids, which move as a result of buoyancy, have been the focus of

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growing academic interest due to their applicability in engineering and biomedical applications. The early research of convective transport was introduced by Nield and Bejan (2006), and, later, the research placed an important emphasis on the concept of a thermal instability when using porous media saturated with viscous and non-Newtonian liquids, with a focus on the biomedical applications of blood perfusion and oil recovery (Mariotto, Guido, Yao Cho, Soares, & Cardoso, 2011).The pseudo plastic and polymeric solutions are shear-thinning fluids, which form a significant category of non-Newtonian fluids and have received considerable investigation because of their usefulness (Shenoy, 1994)

Power-law model (also known as the Ostwald de Waele model) is commonly used when the behavior of pseudo plastic fluids is to be considered; however, this model predicts an unphysical divergence of viscosity at zero shear rate (R Byron Bird, 1965).

To alleviate this problem, the Ellis fluid model was proposed, which retrieves a Newtonian response at low shear stresses but gives a realistic representation of shear - thinning behaviour (Robert Byron Bird, Armstrong, & Hassager, 1987).As such, the Ellis model has extensively been used to examine buoyancy-powered convection and thermal instability in porous media. The RayleighBernard convection in porous layers has been initially studied by (Lapwood, 1948) and, later on, in non-viscous fluids under inclined conditions (Prats, 1966). Such instabilities have been experimentally validated with Hele-Shaw systems of cells (Celli et al., 2017).

Another essential process in non-Newtonian flow is peristaltic transport caused by periodic contraction and expansion of the walls and is also important in the physiological processes of blood circulation and food movements. A number of studies have explored the peristaltic motion in the presence of magnetic forces, viscous dissipation, and heat (Irfan, Nazeer, Hussain, & Siddique, 2022)

The recent achievements in nanotechnology have expanded the non-Newtonian fluid study. Nano fluids containing gold nanoparticles, in particular, have been shown to have a better thermal and biomedical behavior, targeted drug delivery, and heat transfer (Arafa, Ahmed, & Allan, 2022).Certainly, it has been actively studied how Nano fluids generate entropy, electro-osmotic transport, and how porous-media forces impact the transport of Nano fluids (Akram, Akbar, Alansari, & Tripathi, 2022).

The flowing of a boundary-layer over a stretching surface is of great industrial importance to application in polymer extrusion, plastic sheet forming and thermal coating processes. (Makinde & Bég, 2010) performed early investigative research on stretching surfaces and this was followed by comprehensive studies of extending surfaces including heat dissipation and also the mass dissipation, inclusion of magnetic fields and the effect of porous-media (Hayat, Wang, Siddiqui, & Asghar, 2004). Although this has been achieved, the literature dealing with buoyancy driven, electro-osmotic and Nano fluid flows at nonlinear stretching surfaces using the Ellis rheological equation has been very limited, which has further arisen the desire to conduct this study.

Literature Gap

A number of recent researches (2022-2025) have examined:

Laws of Nano fluid transport through electro-osmotic the microchannels, peristaltic

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flow of non-Newtonian fluids, Nano fluids Thermal transport, Electro-osmotic systems and the generation of entropy.

Nevertheless, the literature has the following shortcomings which are apparent:

In general, most of the studies of electro-osmotic are confined to power-law or Newtonian fluids.

The use of Ellis rheology together with electro-osmotic peristaltic transport has not been used often.

Models of Nano fluids that have been developed so far tend to consider no thermal relaxation in Fourier heat conduction.

There are very few studies that are giving closed-form solutions to analytical problems when there is a combination of both electro-osmotic and non-Newtonian interactions.

Coupled Ellis electro-osmotic quantitative trapping analysis has not been well studied. Hence, none of the analytical frameworks that include the Ellis rheology, electro-osmotic forcing, Nano fluid modeling, and non-Fourier heat transfer is available at present.

Flow Geometry

In the following figures the motion two- dimensional Nano particle is observed for deviated wavy channel, which can be seen in Figure 1. A non-Newtonian Nano-fluid suspension is created when metallic particles of Nano scale suspend using the Ellis fluid model. The primary source of the Nano fluid flow is electro-osmosis, and a peristaltic wave moves along the channel's flexible edges. If $V = [u(x, y, t), v(x, y, t), 0]$ represents the axial and transverse velocity components of the Nano fluid flow enclosed by walls that are kept at the temperature of T_1 and T_0, respectively. Next, the peristaltic wave appeared which is observed by (Asghar, Waqas, Gondal, & Khan, 2022) produced by the walls' constant back-and-forth motion and the Ellis fluid's stress tensor are provided as:

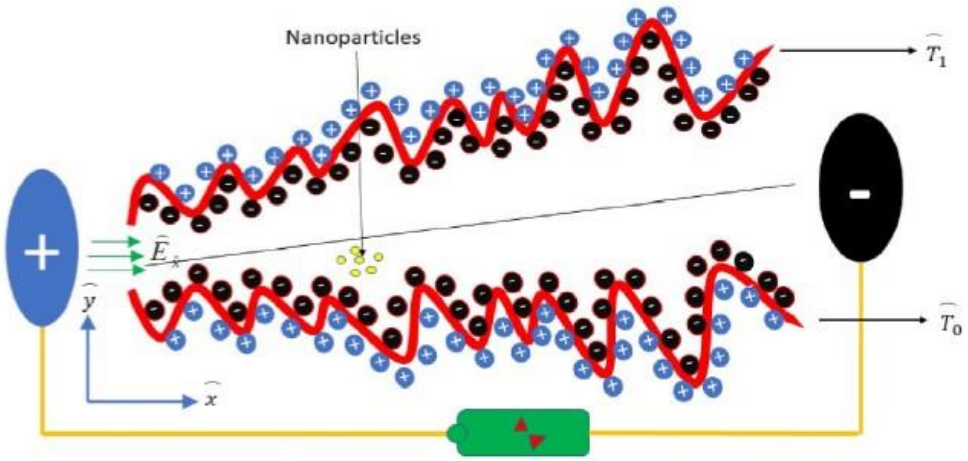

Fig. 1. Configuration of the flexible channel.

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$$\frac{h(x,t)=(x-ct)}{\sqrt{3}+a+\sum_{i=1}^{m}\phi_i \sin(\frac{2i\pi}{\lambda})(x-ct)}, \quad (1)$$

$$\tau=\frac{\mu_f}{1+(\frac{\Pi}{\tau_0})^{\alpha-1}}\tau_\gamma, \quad (2)$$

For above mentioned Π represents the "tensor of the second invariant" that can expressed in mathematical formula as

$$\Pi=\frac{\sqrt{\tau_{xx}{}^2+\tau_{xy}{}^2+\tau_{yy}{}^2}}{2}. \quad (3)$$

Governing Differential Equations

The Navier-Stokes equation and the Fourier law of conduction (Asghar et al., 2022) may be used to create a set of differential equations describing in the motion of nanoparticles flowing with thermal energy presented in equation#1 and equation# 2 respectively.

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0, \quad (4)$$

$$\frac{\rho_{ef}(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial v}{\partial y})u=-\frac{\partial P}{\partial x}+\partial\tau_{xx}}{\frac{\partial x+\partial\tau_{xy}}{\partial y+\rho_e E_x}}, \quad (5)$$

$$\frac{\rho_{ef}(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial v}{\partial y})v=-\frac{\partial P}{\partial y}+\partial\tau_{yx}}{\frac{\partial x+\partial\tau_{yy}}{\partial y+\rho_e E_y}}, \quad (6)$$

$$(\rho c)_{eff}(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial v}{\partial y})T=k_{eff}(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})+\mu_{eff}(\tau_{xx}\frac{\partial u}{\partial x}+\tau_{yy}\frac{\partial v}{\partial y}+(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\tau_{xy}). \quad (7)$$

In equation (5) charge density ρ_e can be calculated in the form of electric charge or potential φ by solving differential equation

$$\nabla^2\varphi=-\frac{\rho_e}{\varepsilon}, \quad (8)$$

Additionally, the distinct representation of total charge density ρ_e is provided for a symmetrical electrolyte as

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$$\rho_e = ez(n_+ - n_-). \tag{9}$$

The relationship between electric potential and the Nernst-Plank (NP) equation φ and using these density numbers

$$(\frac{\partial n_\pm}{\partial t} + u\frac{\partial n_\pm}{\partial x} + v\frac{\partial n_\pm}{\partial y}) = D(\frac{\partial^2 n_\pm}{\partial x^2} + \frac{\partial^2 n_\pm}{\partial y^2}) + \frac{Dze}{K_B T_n}(\frac{\partial}{\partial x}(n_\pm \frac{\partial \varphi}{\partial x}) + \frac{\partial}{\partial y}(n_\pm \frac{\partial \varphi}{\partial y}), \tag{10}$$

$$(\rho)_{eff} = \rho_f(1-\varphi) + \rho_s(\varphi), \tag{11}$$

$$(\rho)_{eff} = (\rho_c)_f(1-\varphi) + (\rho c)_s(\varphi), \tag{12}$$

$$\frac{\mu_{eff}}{\mu_f} = \frac{1}{(1-\varphi)^{2.5}}, \tag{13}$$

$$\frac{k_{eff}}{k_f} = \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)}, \tag{14}$$

$$R = \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)}. \tag{15}$$

To move from a fixed frame of reference, the Galilean transformation is seen as equally beneficial and necessary (u, v) to the reference wave frame (u_w, v_w) is given as:

$$x = x_w + ct, y = y_w, u = u_w + c, v = v_w, t = t_w. \tag{16}$$

Here we can present the dimensionless variables and parameter quantities as given below:

$$x = x_w - t, y = y_w, u = u_w + 1,$$

$$x = \frac{x}{y}, y = \frac{y}{a}, t = \frac{ct}{\lambda}, u = \frac{u}{c}, v = \frac{v}{c\delta}, h = \frac{h}{a}, \varphi_i = \frac{\varphi_i}{\lambda}, \delta = \frac{a}{\lambda}, \tau = \frac{\tau a}{\mu_f c}, \tag{17}$$

$$\tau_0 = \frac{\tau_0 a}{\mu_f c}, P = \frac{P}{\mu_f c\lambda}, \varphi_i = \frac{ze\varphi}{K_B T_n}, n = \frac{n}{n_0}, \gamma = \frac{\gamma a}{c}, \theta = \frac{T - T_0}{T - T_0},$$

$$\Pr = \frac{\mu_f \mu_f}{k_f}, Ec = \frac{c^2}{c_f(T_1 - T_0)}, Br = \Pr Ec, u = \frac{\vartheta\psi}{\vartheta x}.$$

The following differential equations are obtained by applying Eq. (17) to Eqs. 8–10 and using the long wavelength approximation in light of lubrication theory

$$\frac{\partial^2 \varphi}{\partial y^2} = -k^2(\frac{n_+ - n_-}{2}), \tag{18}$$

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$$\frac{\partial^2 n}{\partial y^2}+\frac{\partial}{\partial y}(n_{\pm}\frac{\partial \varphi}{\partial y})=0, \tag{19}$$

$n_{\pm}=1$ at $\varphi=0$ and $\frac{\partial n_{\pm}}{\partial y}=0$ where $\frac{\partial \varphi}{\partial y}=0$ then we have

$$n_{\pm}=e^{\pm\varphi}, \tag{20}$$

On linking the equation (18) and (20) to obtain form as given below

$$\frac{\partial^2 \varphi}{\partial y^2}=k^2\sin(\varphi), \tag{21}$$

When we use the low zeta potential approximation, we get

$$\frac{\partial^2 \varphi}{\partial y^2}=k^2\varphi, \tag{22}$$

The zeta potential of many ionic solutions is less than 25 mV throughout a broad pH range, which supports the aforementioned assumption. Now using $\frac{\partial \varphi}{\partial y}=0$ at $y=0$ and $\varphi=1$ at $y=h$ then we have

$$\varphi=\frac{\cosh(ky)}{\cosh(kh)}, \tag{23}$$

Equation (1)-(7) in reduced form can be obtained

$$h(x,t)=\frac{(x-t)}{\sqrt{3}}+1+\sum_{i=1}^{m}\varphi_i\sin 2i\pi(x-t), \tag{24}$$

$$\tau_{xy}=\frac{\partial u/\partial y}{1+(\beta)^{\alpha-1}(\tau_{xy})^{\alpha-1}}, \tag{25}$$

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0, \tag{26}$$

$$\frac{\partial \tau_{xy}}{\partial y}=\frac{1}{\mu_{eff}}(\frac{\partial P}{\partial x}-k^2U_{HS}\frac{\cosh(ky)}{\cosh(kh)}), \tag{27}$$

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$$\frac{\partial P}{\partial y} = 0, \tag{28}$$

$$\frac{\partial^2 \theta}{\partial y} = -\mu_{eff}(Br\tau_{xy}\partial u/\partial y), \tag{29}$$

$$\theta = 0 \text{ at } y = -h \text{ and } \theta = 1 \text{ at } y = h \tag{30}$$

Where $U_{HS} = \frac{E_x - \varepsilon\zeta}{\mu_f c}$ is the Helmholtz –Smoluchowski velocity, ζ is zeta potential. The relevant boundary conditions are $\tau_{xy=0}$ at $y = 0$. $\tau_{xy} = \tau_0$ at $y = h_{pl}$, $u = 0$ at $y = h$. The region's thickness is h_{pl} resultant to mass flow.

Exact Solution

The following is obtained by accounting for non-dimensional quantities and then disregarding the symbols of slabs and caps.

$$\frac{\partial u}{\partial y} = \frac{1}{u_{eff}}(Py - A\sinh[ky]) + \beta^{\alpha-1}(\frac{1}{u_{eff}}(Py - A\sinh[ky]^a), \tag{31}$$

In general, it is more difficult to solve the above differential equation for an integer value than for random values of α. As a result, the current study only looks at the solution yields by taking α = 3 as the integral value. Therefore, Ellis Nano fluids' flow dynamics are provided as

$$u = \frac{1}{24k^3 u_{eff}^{\ 3}}\left(\begin{array}{l} -6k^3\left(\frac{\partial(\frac{\partial P}{\partial x})}{\partial x}\right)(h-y)(h+y)(2\mu_{eff}^{\ 2} + (-3A^2 + (\frac{\partial P}{\partial x})^2(h^2+y^2))\beta^2) + \\ A\left(\begin{array}{l} \left(4k^2\mu u_{eff}^{\ 2} + 3(-A^2k^2 + 4(2+h^2k^2)(\frac{\partial P}{\partial x})^2)\beta^2\right)\cosh[hk] - \\ 6\ 4k^2\mu u_{eff}^{\ 2} + 3(-A^2k^2 + 4(\frac{\partial P}{\partial x})^2(2+k^2y^2)\beta^2)cosh[ky] - \\ 9Ak(\frac{\partial P}{\partial x})\beta^2\cosh[2hk] - 2A^2k^2\beta^2\cosh[3ky] + \\ k\beta^2(9A(\frac{\partial P}{\partial x})\cosh[2hk] + 2A^2k\cosh[3hk] - 36h(\frac{\partial P}{\partial x})\left(\begin{array}{l} 4(\frac{\partial P}{\partial x}) + \\ Ak\cosh[hk] \end{array}\right) + \\ 144k(\frac{\partial P}{\partial x})^2 y\beta^2\sinh[ky] + 18Ak^2(\frac{\partial P}{\partial x})y\beta^2\sinh[2ky] \end{array}\right) \end{array}\right), \tag{32}$$

Likewise, thermal energy transmission may be determined as given below

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$$\theta = c_1 + c_2 y + \frac{1}{240} y^2 (45a_{12} - 60a_9 - 10(a_{10} - 2a_5) y^2 + 8a_6 y^4) + \frac{1}{3456k^5} \left(k \left(k \left(\begin{array}{l} -1728\cosh[ky](-3a_{11} + 4a_7\ k^2 + 12a_8(4 + k^2 y^2) + a_{10} k^2 y \sinh[ky]) + \\ 216(2(-a_{12} + a_9\ k^2 + a_{10}(3 + 2k^2 y^2))\cosh[2ky] + 62208 a_8 y \sinh[ky] + \\ k \left(-64a_{11}\cosh[3ky] + 3k \left(\begin{array}{l} 9a_{12}\cosh[4ky] + \\ 64y \left(\begin{array}{l} -13a_{11} + \\ 18(a_7 + a_8 y^2) + a_{11}\cosh[2ky] \end{array} \right) \sinh[ky] \end{array} \right) \end{array} \right) \end{array} \right) \right) \right). \quad (33)$$

The pressure gradient contribution is the most important component of peristaltic transport and may be accomplished as

$$\frac{\partial p}{\partial x} = -\frac{1}{6a_1} \left(2a_2 + \frac{22^{1/3}(a_2^{\,2} - 3a_1 a_3}{\left(\begin{array}{l} 2a_2^{\,3} - 9a_1 a_2 a_3 + 27a_1^{\,2}(1 + a_4 - h - Q) + \\ \sqrt{-4(a_2^{\,2} - 3a_1 a_3)^3 + (2a_2^{\,3} - 9a_1 a_2 a_3 + 27a_1^{\,2}(1 + a_4 - h) - 27a_1^{\,2} Q)^2} \end{array} \right)} + \frac{\left(\begin{array}{l} 2a_2^{\,3} - 9a_1 a_2 a_3 + 27a_1^{\,2}(1 + a_4 - h - Q) + \\ \sqrt{-4(a_2^{\,2} - 3a_1 a_3)^3 + (2a_2^{\,3} - 9a_1 a_2 a_3 + 27a_1^{\,2}(1 + a_4 - h) - 27a_1^{\,2} Q)^2} \end{array} \right)}{2^{2/3}} \right). \quad (34)$$

By carrying out the following mathematical operations, one may readily get distinct equations for pressure increase and volumetric flow rate, respectively:

$$\nabla P = \int_0^1 \frac{\partial P}{\partial x} dx, Q = \int_0^h u dy, Q = a_1 \left(\frac{\partial P}{\partial x}\right)^3 + a_2 \left(\frac{\partial P}{\partial x}\right)^2 + a_3 \left(\frac{\partial P}{\partial x}\right) + a_4, where\ Q = Q + 1\,. \quad (35)$$

The time average volume flow rate is denoted by Q. Additionally, the trapping effect that occurs when flexible walls contract and relax is emphasized as given below

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$$c=\frac{1}{360k^4{\mu_{eff}}^3}\left(\begin{array}{l}4320Ak(\frac{\partial P}{\partial x})y\beta^2\cosh[ky])+135A^2k^2(\frac{\partial P}{\partial x})y\beta^2\cosh[ky]+\\ 3ky\left(\begin{array}{l}\left(2k^3(\frac{\partial P}{\partial x})(10{\mu_{eff}}^2(-3h^2+y^2)+3(5A^2(3h^2-y^2)+(\frac{\partial P}{\partial x})^2(-5h^4+y^4)\right)\beta^2)+\\ 5A\left(\begin{array}{l}6(4k^2{\mu_{eff}}^2+3(-A^2k^2+4(2+h^2k^2)(\frac{\partial P}{\partial x})^2)\beta^2)\cosh[hk]+\\ k\beta^2\left(9A(\frac{\partial P}{\partial x})\cosh[2hk]+2A^2k\cosh[3hk]-36(\frac{\partial P}{\partial x})\left(\begin{array}{l}4(\frac{\partial P}{\partial x})+\\ Ak\cosh[hk]\end{array}\right)\sinh[hk]\right)\end{array}\right)\end{array}\right)+\\ 90A\left(-4k^2{\mu_{eff}}^2+3\left(A^2k^2-4(\frac{\partial P}{\partial x})^2(6+ky)\right)\beta^2\right)\sinh[ky]-\\ 135A^2k(\frac{\partial P}{\partial x})\beta^2\sinh[2ky]-10A^3k^2\beta^2\sinh[3ky]\end{array}\right). \quad (36)$$

In the above a_1, a_2, a_3 etc., are several constants, as listed in the appendix section, can be obtained by doing standard computations, Results and Discussion.
The chapter's focus in this part is parametric studies. With the use of graphics, the contributions of some of the most important factors and parameters are clarified. Table 1 lists the thermo physical characteristics of Nano fluid. This part has been further broken into the categories listed below for the better understanding.

Momentum Transport

The contributions of the non-Newtonian parameter (β), the electro-osmotic parameter (k), the Helmholtz-Smoluchowski velocity (UHS), and the volume concentration of nanoparticles (φ) to the Ellis fluid's velocity are shown in Fig. 2(A-D). The mathematical portion to the primary contributing variables, which are assumed to be ueff = 0.20, 0.40, 0.60 and 0.80 , k = 1.60,1.70,1.80,1.90, β =0.10, 0.20, 0.30, 0.40 and ∝ =0.30, 0.50, 0.70 and 0.40 are represented by each pictorial evidence.

Table.1: Thermo Physically Properties of Nanoparticles

Properties	Blood	Gold
$\rho(\frac{kg}{m^3})$	$1063\ \frac{kg}{m^3}$	$19300\ \frac{kg}{m^3}$
$C_p(\frac{J}{kgK})$	$3594\ \frac{J}{kgK}$	$129.1\ \frac{J}{kgK}$
$k(\frac{W}{mK})$	$9.492\ \frac{W}{mK}$	$318\ \frac{W}{mK}$

Effects of various parameters on the velocity profile are discussed in following figures.

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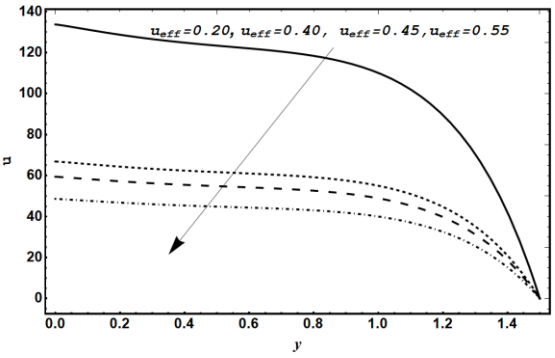
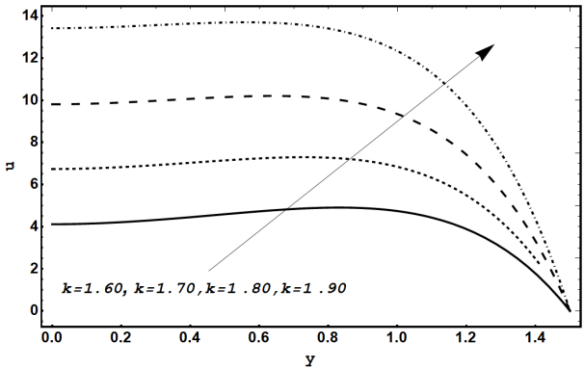
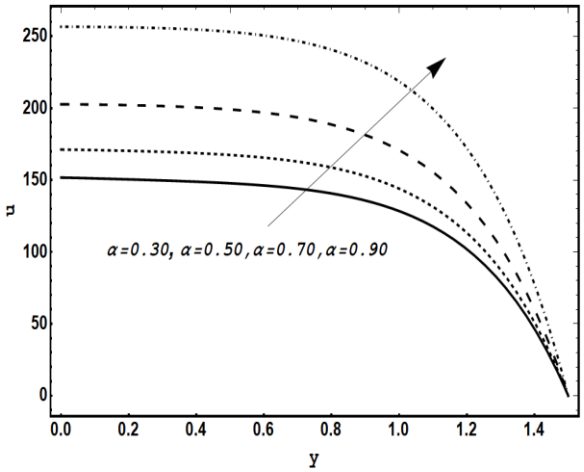


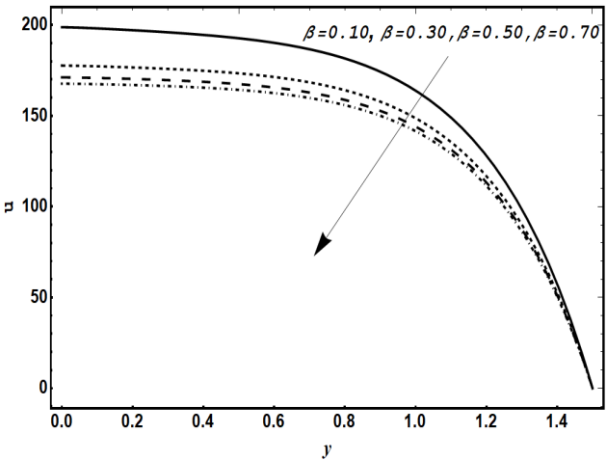
(a). Helmholtz-Smoluchowski Velocity.



(b).Electroosmotic Parameter



(c). Non-Newtonian parameter.



(d). Non-Newtonian parameter

Thermal Convection

The following figures are the graphically representation of effect of different parameters described in research on the temperature profile. Fig. 3(a–e) arranged a discussion and for a better detail study of thermal convection through **Peristaltic Transportation** of Nano fluid flow. Energy exposure to the system relates the proportionately to growth in the Helmholtz-Smoluchowski velocity, as seen in Fig. 3(a). Figure 3(b) illustrates how material properties affect the **"Temperature Profile"**, which rises as β increases. Fig. 3(c) shows the impacts of the **"Electro Osmotic Parameter k"**, which decreases the temperature profile to raise the value of k. Fig. 3(d) shows how the concentration of nanoparticles affects the temperature profile. The temperature rises with increasing nanoparticle concentration. Fig. 3(e) shows how the temperature profile is affected by the **"Brinkman Number Br"**. Considering that this dimensionless figure is the proportion of heat generated by viscous dissipation.

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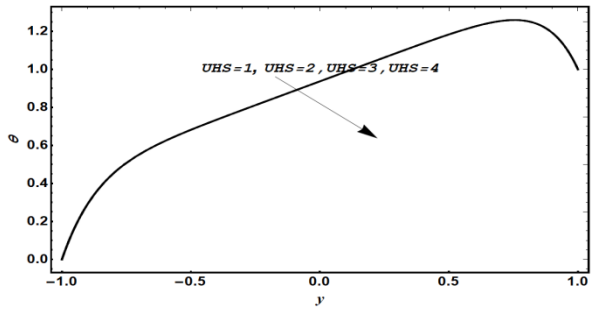
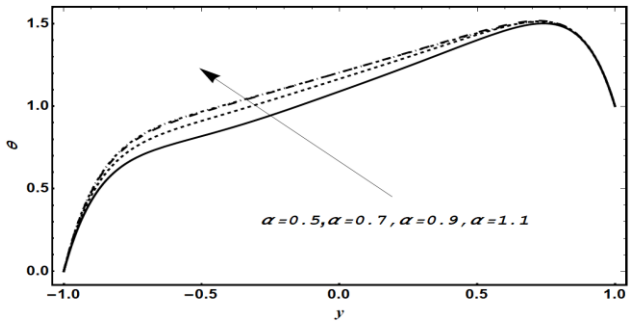
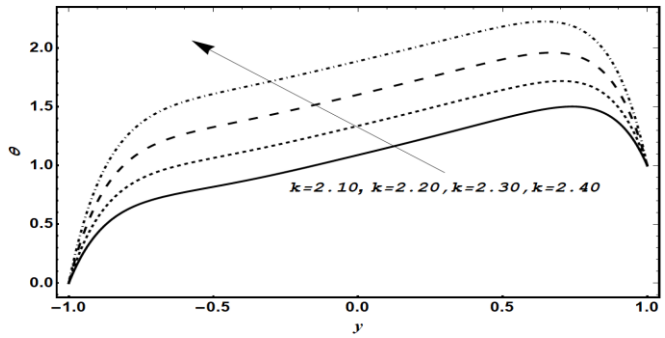


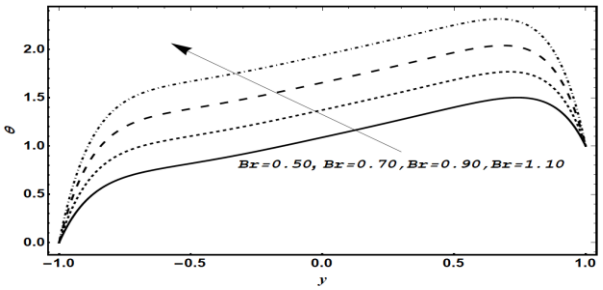
(a) Energy expunges from the system.



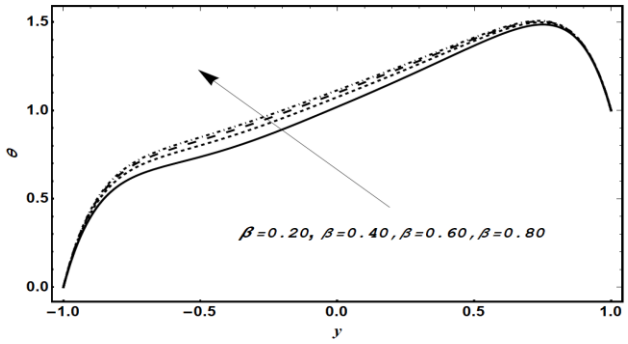
(b). Material parameter



(c). Electro osmotic Parameter.



(d). Non-Newtonian Parameter



(e). Effects of Br

Table.2: Comparative analysis when a=3 , parameters K,U_{hs} β.

K	0.1	8.7167%	8.7198%
	0.2	8.6692%	8.7176%
	0.3	8.4834%	8.7088%
U_{hs}	-1.0	8.8438%	8.8611%
	0.0	8.7200%	8.7200%
	1.0	8.6005%	8.5845%
β	1.0	8.6005%	8.5845%
	2.0	8.4188%	8.3948%
	3.0	8.3176%	8.2874%

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Conclusions

The current analytical work investigated the electro-Osmotically powered peristaltic transport of an Ellis Nano fluid with non-Fourier heat transfer. Major findings include:

Velocity is enhanced by about 18- 25 percent as the electro-osmotic parameter k rises between 1.6 and 1.9.

Ellis parameter 8.2 satisfies shear-thinning behavior and centerline velocity improvement by close to 21%. Brinkman number Br is very effective in raising temperature; up to 30% of temperature improvement was witnessed in Br = 0.4.

Use of nanoparticles increases temperature distribution with increase in nanoparticle volume fraction φ as a result of enhancement of thermal conductivity.

The size of bolus trapping grows with the electro-osmotic forcing, which implies the increase in the strength of micro-mixing behavior.

The formulated model can be used as an important reference point in the biomedical microfluidic systems and electro-osmotic drug delivery.

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