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Research Article

Peristaltic Effects on Flow of Hybrid Nanofluid in an Elliptic Duct With Elasticity

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Abstract. This paper is focused on a hybrid nanofluid in an elliptic duct. The walls of the elliptical duct have two specific properties which include sinusoidal movement and elastic behavior. Elastic property is included in the model with the help of tension and radius relationships in two different ways. The cu/Ag/water hybrid nano model is considered in the present work. The equations governing the flow are resolved by the closed form technique. Comparison between two different combinations of nanoparticles is done graphically. The impact of elasticity, inlet pressure, outlet pressure, amplitude ratio, and other physical parameters on the flux of the nanofluid is observed. The elastic property of the wall is the innovative thought used in the present work and it finds its applications in the field of medicine.

Keywords. Elasticity, Inlet pressure, Outlet pressure, Elliptical duct, Hybrid nanofluid, Sinusoidal wave

Mathematics Subject Classification (2020). 74B10, 76A05, 76Z05

1. Introduction

In recent days, transplantation of organs in the human body is quite common. There are many reasons for arteries to get damaged. Most cases are due to existing food habits formation of fatty plaque in blood vessels is a major issue. Apart from this, due to accidents which are increasing day-by-day artery, vein and vessel get damaged. The replacement of an artery, vein or vessel is a well known fact. Transplantation is done in two ways: one is to replace artery/vein/vessel from the patient's other body parts, and other is to replace the damaged artery/vein/vessel with artificial organ. If the damaged artery is replaced by the patient's other body parts, then there is a chance of arteriosclerosis and some post-surgical complications. To avoid these complications, it is preferred to go for artificial organ replacement. Researchers developed artificial organs and tested them on animals for months and they succeeded. The use of artificial organs has been done for the past ten years. There are three different types of artificial organs produced: (i) fully automated, (ii) semi-automated, and (iii) hand-worked. Every job has its advantages and disadvantages. To overcome some of the disadvantages, it is necessary to study the behavior of arteries more effectively. There are many parameters to be concentrated among which the elastic property of the artery is the key point to be noted. It is observed that most human organs are elastic.

Haseena *et al*. [4] worked on the flow of a nanofluid in an artery in the presence of elasticity. We discussed the impact of copper, aluminum, and titanium oxide nanoparticles on the elastic vertical tube. Fluid flow in a channel with an inner wall as rigid and an outer wall as elastic behavior is concentrated by Oskuei *et al*. [7]. Shahzad *et al*. [11] concentrated on the flow of biomagnetic blood flow in a stenosed artery bounded by elastic walls. Two models are concentrated by Vajravelu *et al*. [12] and comparisons between the two models are done graphically for Casson fluid. Non-Newtonian Herschel-Bulkley fluid was modeled as blood in a capillary with elastic properties by Vajravelu *et al*. [13].

The wave passing from lower pressure to higher pressure is called a peristaltic wave. It is an established fact that human organs are regularly subjected to such waves. This peristaltic wave can be of any defined form as cosine, sine, triangular, square, alpha, theta, etc. as per the position of the human body. For example, alpha wave will occur in the human brain if the person is relaxed and calm, but theta waves will occur in the human brain if the person is sleepy. The sine wave or sinusoidal wave is the basic wave for the generation of other waves in the human body. An accepted fact among medical researchers is that every organ in the human body is under vibration constantly. Based on this fact any research work on human organs must include sine waves as a basic representation of vibration to reach real applications.

Peristaltic impact on the flow with heat transfer for high values of Reynolds number is studied by Javed *et al*. [5]. The finite element approach is used to solve governing equations and results are discussed briefly. Ali *et al*. [2] studied Jeffrey fluid flow in an asymmetric channel in the presence of wavy walls. They solved governing equations with the help of the asymptotic analysis technique. Rajshekar *et al*. [8] concentrated on the peristaltic impact on Jeffrey fluid flow through a microchannel with wall and variable fluid properties. Akhtar *et al*. [1] found a closed form solution for a flow in a wavy wall boundary elliptical duct.

The study of nanoparticles is a hot topic in the present world of research because of its wide applications in various fields. The present paper deals with the applications of nanoparticles in the field of biology and medicine. If a medicine is taken by a patient for a particular disease it will pass through the bloodstream. Blood will carry medicine to other parts of the body and works on the part required effectively. Before medicine reaches the desired part, it must cross other body parts which results in some side effects that may lead to serious health issues as per the patient's health condition. To avoid this critical situation there are many drug delivery systems adopted so far. Even then there are certain challenges to be crossed, so the current medical field in using nanoparticles to deliver the drug at an appropriate site is one of the techniques. Biocompatible nanoparticles, nanorobots, biopolymeric nanoparticles, etc. are some of the examples of nanoparticles used in the medical field. There are numerous such nanocarriers with different approaches to drug release at the targeted organ.

A numerical approach to *Hybrid Nanofluid* was done by Shah *et al*. [10] in a cylinder with the impact of porosity and MHD. They used the control volume finite element method, to solve equations governing the fluid flow. Chung *et al*. [3] concentrated on the flow of partially ionized hybrid nanofluid in the presence of thermal stratification. Waini *et al*. [14] concentrated on the flow of nanofluid through a sheet and obtained a solution using the bvp4c technique in MATLAB for both stretching and shrinking cases with suction parameters. Analysis of entropy on the flow of hybrid nanofluid in an elliptic duct was analysed by McCash *et al*. [6] with wave boundaries.

In the present work, we are discussing the impact of copper and aluminum nanoparticles on blood flow under the influence of elasticity and peristalsis. If the drug carriers are made up of copper and aluminum, then how the blood flow under the impact of sinusoidal wave and elasticity will be noticed graphically by solving the governing equations in closed form. The impact of elastic parameters, hybrid nanofluid, amplitude ratio, and inlet and outlet pressure on fluid flow is worked out. There is discussion of interesting facts that will pique the interest of young researchers in the field of drug delivery approach.

2. Mathematical Formulation

A mathematical model of a *Hybrid Nanofluid* in an elliptical duct is studied under the influence of peristalsis and elasticity. The physical representation of the model is given in Figure 1.

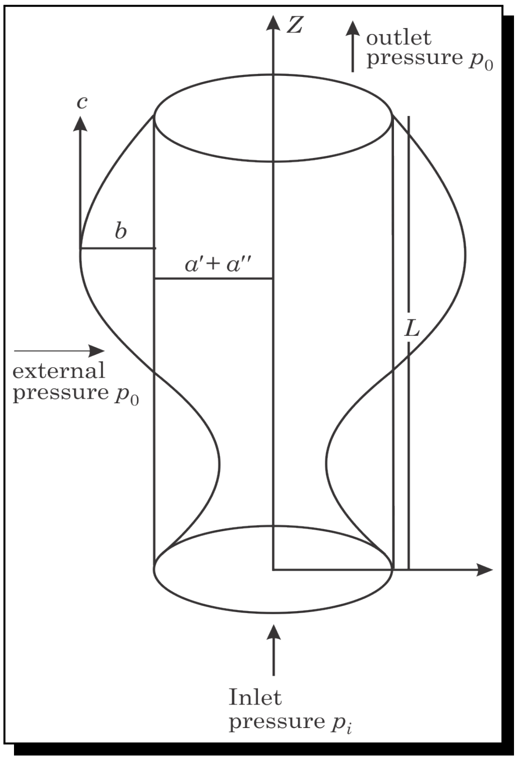

Figure 1. Physical model

The walls of the elliptical duct are peristaltic with the following equations

$$\eta(z,t) = \eta_0 + \varepsilon \sin\left(\frac{2\pi}{\lambda}(z-ct)\right), \tag{1a}$$

$$\xi(z,t) = \xi_0 + \varepsilon \sin\left(\frac{2\pi}{\lambda}(z-ct)\right). \tag{1b}$$

The equations governing the flow are given by

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} + \frac{\partial \bar{w}}{\partial \bar{z}} = 0, \tag{2}$$

$$\rho_{hnf}\left(\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} + \bar{w}\frac{\partial \bar{u}}{\partial \bar{z}}\right) = -\frac{\partial \bar{p}}{\partial \bar{x}} + \mu_{hnf}\left(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{z}^2}\right), \tag{3}$$

$$\rho_{hnf}\left(\frac{\partial \bar{v}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}} + \bar{w}\frac{\partial \bar{v}}{\partial \bar{z}}\right) = -\frac{\partial \bar{p}}{\partial \bar{y}} + \mu_{hnf}\left(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{y}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{z}^2}\right), \tag{4}$$

$$\rho_{hnf}\left(\frac{\partial \bar{w}}{\partial \bar{t}} + \bar{u}\frac{\partial \bar{w}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{w}}{\partial \bar{y}} + \bar{w}\frac{\partial \bar{w}}{\partial \bar{z}}\right) = -\frac{\partial \bar{p}}{\partial \bar{z}} + \mu_{hnf}\left(\frac{\partial^2 \bar{w}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{w}}{\partial \bar{y}^2} + \frac{\partial^2 \bar{w}}{\partial \bar{z}^2}\right). \tag{5}$$

The appropriate boundary condition is

$$\bar{w} = 0, \quad \text{for } \frac{\bar{x}^2}{\eta^2} + \frac{\bar{y}^2}{\xi^2} = 1. \tag{6}$$

For frame reference

$$\bar{x} = \bar{X},\ \bar{y} = \bar{Y},\ \bar{z} = \bar{Z} - ct,\ \bar{p} = \bar{P},\ \bar{u} = \bar{U},\ \bar{v} = \bar{V},\ \bar{w} = \bar{W} - c. \tag{7}$$

Non-dimensional terms

$$\left.\begin{aligned} &x = \frac{\bar{x}}{Hd},\ y = \frac{\bar{y}}{Hd},\ z = \frac{\bar{z}}{\lambda},\ t = \frac{c\bar{t}}{\lambda},\ w = \frac{\bar{w}}{c},\ p = \frac{Dh^2\bar{p}}{\mu_p \lambda c}, \\ &\delta = \frac{\xi_0}{\eta_0},\ \phi = \frac{\varepsilon}{\xi_0},\ u = \frac{\lambda \bar{u}}{Hdc},\ v = \frac{\lambda \bar{v}}{Hdc},\ \eta = \frac{\bar{\eta}}{Hd},\ \xi = \frac{\bar{\xi}}{Hd}. \end{aligned}\right\} \tag{8}$$

Hd denotes hydraulic diameter represented by

$$Hd = \frac{\pi b_0}{E(e)},$$

where $E(e) = \int_0^{\pi/2} \sqrt{1 - e^2 \sin^2\beta}\, d\beta$ and $e = \sqrt{1-\delta^2}$.

The non-dimensional governing equations, under the assumption of flow, is steady along the z-axis and are given by

$$\frac{\partial p}{\partial x} = 0, \tag{9}$$

$$\frac{\partial p}{\partial y} = 0, \tag{10}$$

$$\frac{dp}{dz} = \frac{\mu_{hnf}}{\mu_f}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right). \tag{11}$$

The non-dimensional boundary condition is

$$w = -1, \quad \text{for } \frac{x^2}{\eta^2} + \frac{y^2}{\xi^2} = 1, \tag{12}$$

where

$$\left.\begin{aligned} \eta &= \frac{E(e)}{\pi}\left[\frac{1}{\delta}+\varphi\sin(2\pi z)\right], \\ \xi &= \frac{E(e)}{\pi}[1+\varphi\sin(2\pi z)]. \end{aligned}\right\} \tag{13}$$

Table 1. Thermophysical properties of the base fluid and nanoparticles [6]

Physical parameters	Base fluid	Nanoparticles	
	(water)	Cu (s_1)	Ag (s_2)
$C_p\left(\frac{J}{kg.K}\right)$	4179	385	235
$k\left(\frac{W}{mK}\right)$	0.52	401	429
$\rho\left(\frac{kg}{m^3}\right)$	1050	8933	10,500

Table 2. Hybrid nanofluid model [6]

Properties	Nanofluid
Density	$\rho_{hnf} = [(1-\phi_2)\{(1-\phi_2)\rho f + \phi_1\rho_{s1}\}] + \phi_2\rho_{s2}$
Viscosity	$\mu_{hnf} = \frac{\mu_f}{(1-\phi_1)^{2.5}(1-\phi_2)^{2.5}}$
Thermal conductivity	$\frac{k_{hnf}}{k_{bf}} = \frac{k_{s2}+(n-1)k_{bf}-(n-1)\phi_2(k_{bf}-k_{s2})}{k_{s2}+(n-1)k_{bf}+\phi_2(k_{bf}-k_{s2})}$
	$\frac{k_{bf}}{k_f} = \frac{k_{s1}+(n-1)k_f-(n-1)\phi_1(k_f-k_{s1})}{k_{s1}+(n-1)k_f+\phi_1(k_f-k_{s1})}$
Heat capacity	$(\rho C_p)_{hnf} = [(1-\phi_2)\{(1-\phi_1)(\rho C_p)_f + \phi_1(\rho C_p)_{s1}\}] + \phi_2(\rho C_p)_{s2}$

3. Solution in Closed Form

Let

$$w = D_1x^4 + D_2y^4 + D_3x^2y^2 + D_4x^2 + D_5y^2 + D_6. \tag{14}$$

The value $w(x,y)$ given in eqn. (14) is inserted in eqn. (11) and the coefficients x^2, y^2, x^0, y^0 are compared to get

$$\left.\begin{aligned} &12D_1 + 2D_3 = 0, \\ &2D_3 + 12D_2 = 0, \\ &2D_4 + 2D_5 = \frac{\frac{dp}{dz}}{\frac{\mu_{hnf}}{\mu_f}}. \end{aligned}\right\} \tag{15}$$

Also, using eqn. (14) in the boundary condition (12) and comparing the coefficients x^4, x^2, x^0, we have

$$\left.\begin{aligned} &D_1\eta^4 + D_2\xi^4 - D_3\eta^2\xi^2 = 0, \\ &-2D_2\xi^4 + D_3\eta^2\xi^2 + D_4\eta^2 - D_5\xi^2 = 0, \\ &D_2\xi^4 + D_5\xi^2 + D_6 = -1. \end{aligned}\right\} \tag{16}$$

By solving (15) and (16), we get

$$\left.\begin{aligned} &D_1=0,\ D_2=0,\ D_3=0,\ D_4=\frac{\xi^2\frac{dp}{dz}}{2(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)},\\ &D_5=\frac{\eta^2\frac{dp}{dz}}{2(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)},\ D_6=\frac{\eta^2\xi^2\frac{dp}{dz}+2\eta^2\left(\frac{\mu_{hnf}}{\mu_f}\right)+2\xi^2\left(\frac{\mu_{hnf}}{\mu_f}\right)}{2(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)}.\end{aligned}\right\}$$

Using these values in eqn. (14), we have

$$w=-1+\frac{\frac{dp}{dz}\left(\frac{x^2}{\eta^2}+\frac{y^2}{\xi^2}-1\right)\eta^2\xi^2}{2(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)}. \tag{17}$$

Integrating eqn. (17) along the elliptical duct, the non-dimensional flow rate for the non-elastic elliptical duct is given by

$$q=-\eta\xi\pi-\frac{\eta^3\xi^3\frac{dp}{dz}\pi}{4(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)}. \tag{18}$$

4. Theoretical Approaches

We incorporate the elasticity property into the elliptical duct, which causes the walls to contract and expand based on the pressure difference between inside pressure $p(z)$ and outside pressure p_0, respectively. The ducts starting and ending points along the z-axis are 0 and L, with respective pressure as $p(0)=p_1$ and $p(L)=p_2$. Because elasticity exists, conductivity σ_1 is assumed to be a function of pressure difference ($\sigma_1=\sigma_1(p(z)-p_0)$), which is same as conductivity in the absence of elasticity. Now, the flow rate is noted as

$$q+\eta\xi\pi=\sigma_1(p(z)-p_0)\left(-\frac{dp}{dz}\right), \tag{19}$$

where

$$\sigma_1(p(z)-p_0)=\frac{\eta^3\xi^3\pi}{4(\eta^2+\xi^2)\left(\frac{\mu_{hnf}}{\mu_f}\right)}. \tag{20}$$

Integrating eqn. (20) along the length of the duct, we have

$$\int_0^1(q+\eta\xi\pi)dz=\int_{p(1)-p_0}^{p(0)-p_0}\sigma_1(p')dp'. \tag{21}$$

From eqn. (1), we can take $\xi=\eta-\eta_0+\xi_0$, with the help of this relation substituting eqn. (20) in eqn. (21), we have

$$q=-\eta\xi\pi+\frac{\pi}{4\left(\frac{\mu_{hnf}}{\mu_f}\right)}\int_{p_2-p_0}^{p_1-p_0}\frac{\eta^3(\eta-\eta_0+\xi_0)^3}{\eta^2+(\eta-\eta_0+\xi_0)^2}dp'. \tag{22}$$

Eqn. (22) can be simplified if we can find a relation between p' and η, and this can be constructed with an equilibrium condition between tension $T(\eta)$ and η as

$$\frac{T(\eta)}{\eta}=p-p_0. \tag{23}$$

Rubinow and Keller's method [9] experimentally done on a 4 cm long human iliac artery, we have a relation as

$$T(\eta) = t_1(\eta-1) + t_2(\eta-1)^5, \tag{24}$$

where the elastic parameters being $t_1 = 13$ and $t_2 = 300$.
Simplifying eqns. (23) and (24), we get

$$dp' = \frac{t_1}{\eta^2} + t_2\left(4\eta^3 - 15\eta^2 + 20\eta - 10 + \frac{1}{\eta^2}\right) d\eta. \tag{25}$$

Using eqn. (25) in eqn. (22), we have

$$q = -\int_0^1 \eta\xi\pi\, dz + \frac{\pi}{4\left(\frac{\mu_{hnf}}{\mu_f}\right)} \int_{\eta_2}^{\eta_1} \frac{\eta^3(\eta-\eta_0+\xi_0)^3}{\eta^2+(\eta-\eta_0+\xi_0)^2} \left[\frac{t_1}{\eta^2} + t_2\left(4\eta^3 - 15\eta^2 + 20\eta - 10 + \frac{1}{\eta^2}\right)\right] d\eta.$$

On simplifying above equation, we get

$$q = -\int_0^1 \eta\xi\pi dz + \frac{\pi}{4\left(\frac{\mu_{hnf}}{\mu_f}\right)}[(t_1+t_2)I_1 + t_2 I_2],$$

where

$$I_1 = \int_{\eta_2}^{\eta_1} \frac{\eta^4 + 3\eta^3 c_0 + 3\eta^2 c_0^2 + \eta c_0^3}{2\eta^2 + 2\eta c_0 + c_0^2} d\eta,$$

$$I_2 = \int_{\eta_2}^{\eta_1} \frac{1}{2\eta^2 + 2\eta c_0 + c_0^2}[4\eta^9 + A_1\eta^8 + A_2\eta^7 + A_3\eta^6 - A_4\eta^5 + A_5\eta^4 - 10\eta^3 c_0^3]d\eta,$$

$$A_1 = 12c_0 - 15,\ A_2 = 12c_0^2 - 45c_0 + 20,\ A_3 = 4c_0^3 - 45c_0^2 + 60c_0 - 10,$$

$$A_4 = 15c_0^3 + 60c_0^2 + 30c_0,\ A_5 = 2c_0^3 - 30c_0^2.$$

The integrals I_2 can be simplified using MATLAB software.

5. Results and Discussions

A study on the flow of hybrid nanofluid under the effect of elasticity in an elliptical duct is presented in this paper. The impact of physical parameters on flux is studied graphically with the help of origin software.

Figure 2 represents the impact of amplitude ratio on flux along the z-axis. It is noticed that flux increases with the increase in amplitude ratio for a cupper-water nanofluid in the trust graph, but the opposite behavior is observed at the triumph of the graph.

The influence of elastic parameters on flux along the z-axis is observed in Figure 3. It is noted that as the elastic parameter increases flux also increases for a cupper-water nanofluid.

A study on the effect of amplitude ratio on the flux of copper-aluminum water hybrid nanofluid is done in Figure 4. The amplitude ratio impact is shown to be the same for nanofluid and hybrid nanofluid. The flux increases with the increase in amplitude ratio. But it is noted that flux is greater for nanofluid compared to hybrid nanofluid.

The flux of hybrid nano fluid along the z-axis increase with the increase in elastic parameter (Figure 5). When compared to the nanofluid flow, the hybrid nanofluid flow is less.

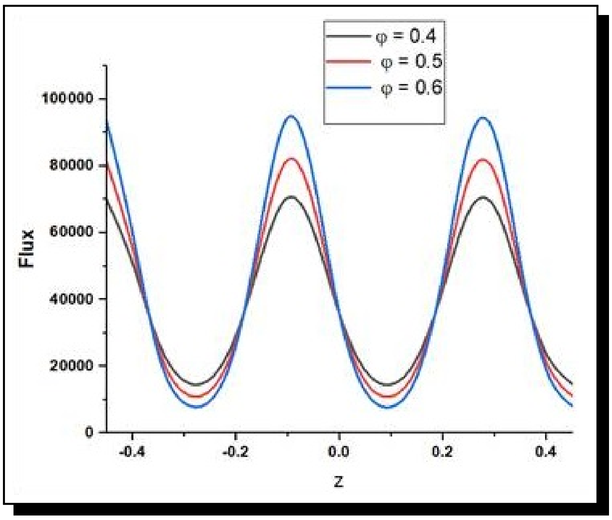

Figure 2. Flux along z for different amplitude ratios for Cu/Water nanofluid

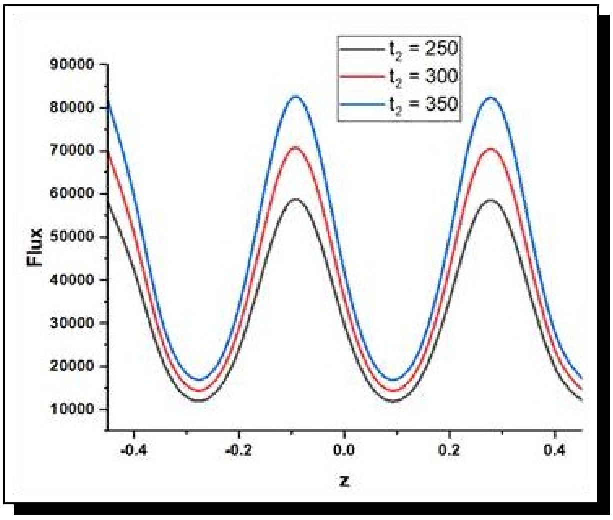

Figure 3. Flux along z for the different elastic parameters for Cu/Water nanofluid

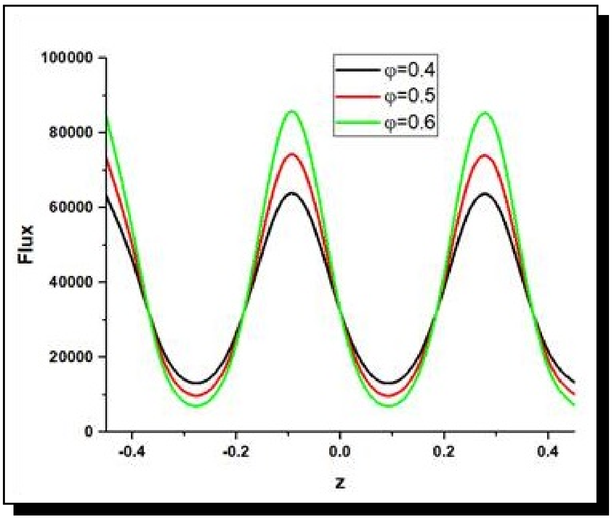

Figure 4. Flux along z for different amplitude ratios for Cu-Ag/Water hybrid nanofluid

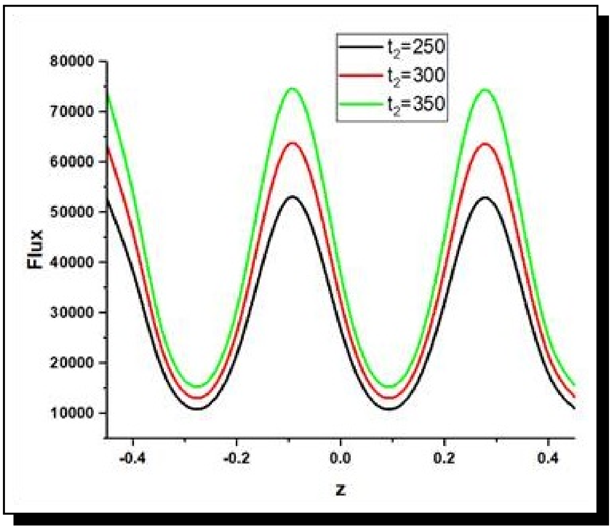

Figure 5. Flux along z for the different elastic parameters for Cu-Ag/Water hybrid nanofluid

Table 3. Flux with z for the different elastic parameters for Cu-Ag/Water hybrid nanofluid

z	$t_1 = 0$	$t_1 = 10$	$t_1 = 20$	$t_1 = 30$
−0.45	63854	63327	62800	62272
−0.40	46628	46153	45677	45201
−0.35	25256	24860	24463	24066
−0.30	14605	14260	13915	13570
−0.25	15097	14749	14401	14054
−0.20	26875	26472	26068	25664
−0.15	48785	48302	47819	47337
−0.10	64355	63827	63298	62770
−0.05	55322	54819	54316	53813
0.00	32785	32357	31930	31503
0.05	17351	16991	16631	16272
0.10	13626	13286	12947	12607
0.15	20712	20336	19960	19583
0.20	39503	39051	38599	38147
0.25	60549	60031	59513	58995
0.30	61798	61276	60755	60233
0.35	41682	41222	40763	40303
0.40	21973	21591	21209	20826
0.45	13795	13454	13114	12773

Table 4. Flux with z for the different elastic parameters for Cu/Water nanofluid

z	$t_1 = 0$	$t_1 = 10$	$t_1 = 20$	$t_1 = 30$
−0.45	70711	70128	69544	68960
−0.40	51636	51109	50582	50055
−0.35	27967	27528	27089	26649
−0.30	16172	15790	15408	15026
−0.25	16717	16332	15947	15562
−0.20	29762	29315	28868	28420
−0.15	54025	53491	52956	52422
−0.10	71269	70684	70099	69513
−0.05	61265	60709	60152	59595
0.00	36307	35834	35361	34887
0.05	19215	18817	18419	18020
0.10	15091	14715	14339	13963
0.15	22939	22522	22105	21689
0.20	43749	43249	42748	42247
0.25	67057	66483	65910	65336
0.30	68440	67862	67285	66707
0.35	46163	45654	45145	44636
0.40	24337	23913	23490	23067
0.45	15280	14903	23913	14149

Tables 3 and 4 show the values for flux with z for different elastic parameters for hybrid nanofluid and nanofluid, respectively. It is assessed that flux increases with the increase of elastic parameters. It is critical to remember that flows in a nanofluid are greater than in a hybrid nanofluid.

Competing Interests

The author declares that she has no competing interests.

Authors' Contributions

The author wrote, read and approved the final manuscript.

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