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Original Article

ENTROPY ANALYSIS IN A CILIA TRANSPORT OF NANOFLUID UNDER THE INFLUENCE OF MAGNETIC FIELD

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ABSTRACT

In this study, analysis is performed on entropy generation during cilia transport of water based titanium dioxide nanoparticles in the presence of viscous dissipation. Moreover, thermal heat flux is considered at the surface of a channel with ciliated walls. Mathematical formulation is constructed in the form of nonlinear partial differential equations. Making use of suitable variables, the set of partial differential equations is reduced to coupled nonlinear ordinary differential equations. Closed form exact solutions are obtained for velocity, temperature, and pressure gradient. Graphical illustrations for emerging flow parameters, such as Hartmann number (Ha), Brinkmann number (Br), radiation parameter (Rn), and flow rate, have been prepared in order to capture the physical behavior of these parameters. The main goal (i.e., the minimizing of entropy generation) of the second law of thermodynamics can be achieved by decreasing the magnitude of Br, Ha and Λ parameters.

1. Introduction

In the last several decades, a number of techniques have been introduced by scientists to boost the efficiency of heat transfer. In this regard, scientists have introduced wavy surfaces, micro channels, and vibration phenomena to heat transfer surfaces. However, the rate of heat transfer can also be upgraded by strengthening the thermal conductivity of conventional fluids. As conventional fluids, such as water, engine oil, lubricants etc., retain limited heat transfer abilities because of low thermal conductivity, they are not capable of meeting modern age cooling needs. On the other side, nanoparticles have dramatically higher thermal conductivity than that of pure fluids. Currently, titanium dioxide has seen potential application in skin care products, cosmetic, sunscreens, etc. Sunscreens are used to protect skin tissues from the harmful radiation of sun. Furthermore, they also reduce the probability of skin tumors, skin smolder, and untimely maturing.

The strength of the thermal nature of nanofluids has key importance in medical science and engineering fields including power generation, transportation, micromanufacturing, pharmaceutical processes, air-conditioning, etc. To be specific, let us consider nanoparticles: titanium dioxide (TiO_2) nanoparticles achieve their best performance in biological, chemical, and environmental engineering, for instance, in drugs, foodstuff, skin goods, toothpastes, paints, nail polishes, plastics, printing inks, and ceramic glazes; these nanoparticles have great potential for remediation of waste water. Based on the above applications of nanoparticles, Choi [1] initially came up with the concept of nanofluids and verified his theory experimentally. Several studies in this direction have been undertaken using different flow conditions: flow induced by linear stretching with convective heating was presented by Makinde and Aziz [2]; stagnation point flow under the influence of porous medium was studied by Alsaedi et al. [3]; Brownian motion and thermophoresis effects over an exponential stretching surface were demonstrated by Nadeem and Lee [4]; characteristics of unsteady flow past an infinite vertical plate were examined by Turkyilmazoglu and Pop [5]; natural convection flow under the action of Lorentz forces was discussed by Sheikholeslami et al. [6]; third grade nanofluid flow in the presence of magnetic field and the Maxwell model for convective cooling were studied by Awais et al. [7,8]; consequences of forced convection

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Nomenclature

nf	Nanofluid
β	Wave number
p	Solid nanoparticles
Θ	Angle of inclination
θ	Dimensionless temperature
Ω	Heat absorption parameter
σ^*	Stefan–Boltzmann constant
ρ_{nf}	Effective density of the nanofluid
ρC_p	Thermal conductivity of the fluid
φ	Solid volume fraction of nanofluid
λ	Wavelength of the metachronal wave
Λ	Dimensionless temperature difference
k_{bf}	Thermal conductivity of the base fluid
ε	Non-dimensional measure with respect to cilia length
μ_{nf}	Effective dynamic viscosity of the nanofluid
α	Measure of the eccentricity of the elliptical motion
bf	Base fluid
B_0	Magnetic field
Gr	Grashof number
Ns	Entropy number
Ha	Hartmann number
$\hbar$	Height of the tube
Rn	Radiation parameter
w	Dimensionless velocity
e	Mean radius of the tube
α_{nf}	Effective thermal diffusivity
k_{nf}	Effective thermal conductivity
$\tilde{T}$	Local temperature of the fluid
$\widetilde{Z_0}$	Reference position of the particle
Q_0	Dimensional heat absorption effect
c	Wave speed of the metachronal wave
k^*	Rosseland mean absorption coefficient

heat transfer in a lid driven semi annuls and natural convection heat transfer in a cubic cavity was presented Sheikholeslami et al. [9,10]; impulsive motion of free convective flow under the influence of thermal heat flux was studied by Das and Jana [11]; mixed convection flow in a symmetric channel was analyzed by Abbasi et al. [12]; and impact of thermal radiation in a stretching cylinder was demonstrated by Hayat et al. [13]. Apart from peristaltic studies, some of the latest studies that deal with magnetohydrodynaimics (MHD) effects for both Newtonian and non-Newtonian fluid are analyzed for various kinds of stretching sheet [14–23].

At present, all heat transfer mechanisms generate entropy. The magnetic, viscous, heat transfer, fall temperature gradient, etc., properties are responsible for the generation of entropy. The entropy generation is associated with the number of energy-related applications such as geothermal power systems, cooling of modern electronic systems, and solar power collectors. Initially, Bejan [24] proposed the theory of entropy generation in heat transfer and fluid flow systems. Some relevant studies on the subject can be seen in the list of references Pakdemirli and Yilbas [25], Aiboud and Saouli [26], Rashidi et al. [27], Galanis and Rashidi [28], Rashidi et al. [29], Ellahi et al. [30], Bhatti et al. [31] and Jamalabadi et al. [32].

The primary focus of this study is to analyze entropy generation during cilia transport under the influence of thermal heat flux and viscous dissipation. In the next sections, author provides an analysis of the problem. Section 3 gives the formulation of entropy generation. An exact solution in closed form for the velocity, temperature, and pressure gradients is presented in Section 4. In Section 5, we discuss the physical sense of the problem through plots and tables. The last section includes the final outcomes of the present study.

2. Analysis

Let us consider ciliary transport of two dimensional, incompressible, and axisymmetric flow of a titanium dioxide water nanofluid in a horizontal tube. The inner surface of the tube is ciliated with metachronal waves. Flow is provoked as a result of these metachronal waves, which are formed due to collective beating of the cilia with constant momentum along the walls of the body. Uniform magnetic field is applied at the angle of inclination (Θ). Heat transfer analysis with the viscous dissipation is also considered. Fig. 1 shows the physical view of the presented model and the coordinates system. The horizontal and vertical velocities of the cilia are given as [33,34]:

$$\tilde{W} = \frac{\left(\frac{-2\pi}{\lambda}\right)\left[ce\varepsilon\alpha\cos\left(\frac{2\pi}{\lambda}\left(\tilde{Z}-c\tilde{t}\right)\right)\right]}{1-\frac{2\pi}{\lambda}\left[e\varepsilon\alpha\cos\left(\frac{2\pi}{\lambda}\left(\tilde{Z}-c\tilde{t}\right)\right)\right]}, \tag{1}$$

$$\tilde{U} = \frac{\left(\frac{2\pi}{\lambda}\right)\left[ce\varepsilon\alpha\sin\left(\frac{2\pi}{\lambda}\left(\tilde{Z}-c\tilde{t}\right)\right)\right]}{1-\frac{2\pi}{\lambda}\left[e\varepsilon\alpha\cos\left(\frac{2\pi}{\lambda}\left(\tilde{Z}-c\tilde{t}\right)\right)\right]}. \tag{2}$$

The following transformation is useful to switch the flow from fixed frame to wave frame.

$$\tilde{r} = \tilde{R}, \quad \tilde{z} = \tilde{Z} - c\tilde{t}, \quad \tilde{u} = \tilde{U}, \quad \tilde{w} = \tilde{W} - c. \tag{3}$$

The fundamental governing equations in the fixed frame for an incompressible nanofluid can be written as:

$$\frac{\partial\tilde{u}}{\partial\tilde{r}} + \frac{\tilde{u}}{\tilde{r}} + \frac{\partial\tilde{w}}{\partial\tilde{z}} = 0, \tag{4}$$

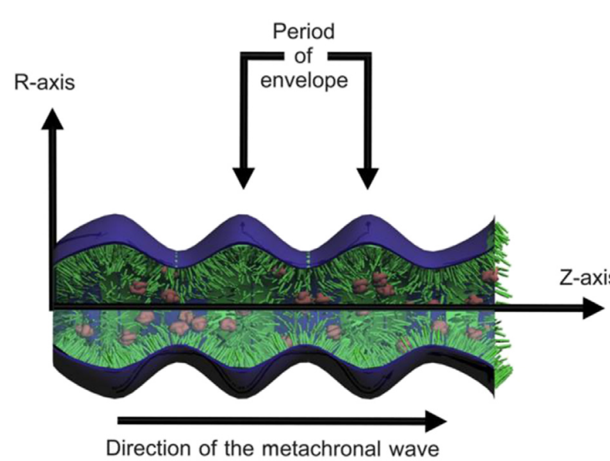

Fig. 1. Geometry of the problem.

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