Entropy generation analysis for metachronal beating of ciliated Cu-water nanofluid with magnetic field

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Abstract: In this paper, we have discussed the entropy generation on the ciliary motion of the peristaltic transport of fluids in human body. On the basis of the mathematical model of the copper nanofluids with pure water as the base fluid, the complete problem is analysed under the presence of heat transfer. It is considered that a group of cilia operate together and produce metachronal waves to transport the fluid. The governing flow equations are non-linear partial differential equations, which are reduced to ordinary differential equation form using the dimensionless variables. The investigation is carried out under the assumptions of low Reynolds number and long wavelength. Exact solutions of the fluid velocity, pressure gradient and temperature profile have been obtained. The obtained expressions are then described through graphs for various relevant parameters. Trapping phenomenon for nanoparticle volume fraction is presented at the end of the paper.

Keywords: peristalsis; magnetic field; nanoparticles; tube flow; entropy; heat transfer; nanofluids; Cu water; metachronal waves; cilia.

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Biographical notes: Noreen Sher Akbar is an Assistant Professor in National University of Sciences and Technology Pakistan. She is a best youngest scientist in Pakistan.

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1 Introduction

The mechanism of peristalsis is to pump the fluids by means of a progressive wave of area contraction and expansion along the walls of a tube containing the fluid. This mechanism causes the fluid to transport by the waves induced during the contraction and expansion. This mechanism is vital from the physiological point of view because peristalsis is used by the body to propel or mix the contents of a tube as in the ureter,
gastrointestinal tract, lymphatic and small blood vessels, reproductive tracts of male and female body, transport of sanitary fluid, etc. Therefore, the analysis of peristaltic flow is worth considering in several systems in the biomedical, biochemical, engineering and industrial fields. In 1966, Latham (1966), a student of Massachusetts Institute of Technology, Cambridge, presented the idea of 'Fluid Motion in a Peristaltic Pump'. He investigated the mechanism of peristalsis in relation to mechanical pumping. His work motivated Shapiro (1967), Fung and Yih (1968) to investigate further the transport of fluid through peristaltic motion. These studies created a new area of research for around the globe. Radhakrishnamacharya (1982) discussed the peristaltic flow in a channel under long wavelength estimation. Mathematical modelling of the peristaltic motion and its analysis through analytical, numerical and experimental approach in various flow geometries has fascinated the attention of many researchers (Akbar, 2013, 2014a, 2014b, 2014c; Mekheimer, 2003; Akbar and Nadeem, 2014; Sheikholeslami et al., 2014).

In the 20th century, a major problem was to solve the increasing temperature in various industrial problems. This was rectified by Choi and Eastman (1995) when he introduced the use of nanoparticles as a mode of enhancing the thermal conductivity of the fluid under consideration. This leads to the study of nanofluids, which are fluids including nanoparticles with unique physical and chemical properties. Such fluids were then used as coolant in several heat transfer problems and natural convection, instead of using oil or water as the working fluid. Recently, great focus is given to the concept of using nanofluids when discussing the heat transfer characteristics in different geometries theoretically and experimentally. With the use of nanofluids, Khanafer et al. (2003) studied the enhancement of buoyancy-driven heat transfer in a two-dimensional enclosure. Koo and Kleinstreuer presented a new thermal conductivity model for nanofluids. Buongiorno (2005) added to the literature and discussed the effect of heat transfer on the transport of nanofluid. Koo and Kleinstreuer (2004), Das et al. (2006, 2007), Jang and Choi (2006), Yu et al. (2008) and Choi (2009) contributed a lot towards the study of nanofluids in different heat transfer problems. To understand the importance of nanofluids in the current era problems, some of the latest significant research papers in the field of nanofluids are cited in Ebaid and Aly (2013), Akbar (2014d), Akbar et al. (2014a), Sheikholeslami and Ghorbani (2014) and Sheikholeslami et al. (2014).

Cilia are small hairlike structures, which help the transport of fluid inside the human body. When a group of cilia operate together, metachronal waves are produced, which apply a force on the fluid to move it in the direction of the effective stroke. These metachronal waves are seen in a sinusoidal pattern. Interesting literature on the envelope approach of cilia and its use as a carriage of fluid can be found in Sleigh (1962), Blake (1971), Sleigh and Aiello (1972), Lardner and Shack (1972) and Akbar et al. (2014b). Recently, Akbar and Butt (2014a, 2014b) explored the heat transfer analysis of peristaltic transport of Cu-water nanofluid in a tube with ciliated walls.

Boltzmann’s concept of entropy change was accepted for a century primarily because skilled physicists and thermodynamicists focused on the fascinating relationships and powerful theoretical and practical conclusions arising from entropy’s relation to the behaviour of matter. There is no basis in physical science for interpreting entropy change as involving order and disorder. The original definition of entropy (change) involves a transfer of heat from a thermal reservoir to a system via a virtually reversible energy flow process (see Peters, 1995; Pakdemirli and Yilbas, 2006; Bianco et al., 2014; Lam and Arul Prakash, 2015; Akpinar and Kavak Akpinar, 2007; Abu-Nada, 2006; Adesanya and Makinde, 2014; Pitchandi, 2014; Makinde et al., 2013).
In view of the above-mentioned discussion, the purpose of current analysis is to investigate the entropy generation analysis of peristaltic flow of a copper nanofluid in a tube under the effect of heat transfer. For a genuine approach towards the problem, the walls of the tube are considered as ciliated with micro-organisms hairlike structures. To the knowledge of the authors, entropy generation of nanofluids with effects of cilia has never been discussed in the literature. To fill this void, we have mathematically formulated the said problem and solved analytically to obtain the exact solutions, which are discussed in the next section with the help of graphs. The physical properties are discussed with respect to significant flow parameters.

2 Problem formulation

Let us consider the peristaltic flow of an incompressible, natural convective peristaltic flow of nanofluids in a horizontal tube. The inner surface of the tube is ciliated with metachronal waves and the flow occurs due to collective beating of the cilia. We represent the geometry of the problem in the cylindrical coordinate system $(R, Z)$ as shown in Figure 1.

Figure 1 Geometry of the problem (see online version for colours)

The problem formulation is based on the following assumption listed here

- flow is incompressible, two-directional and two-dimensional
- walls of the tube are flexible
- metachronal wave pattern propagates along the walls of the tube
- the effect of magnetic field induced by the Reynolds number is sufficiently small to be neglected when compared with the external magnetic field
- because of long-wavelength and low Reynolds number approximation, the velocity component in the $x$-direction is more important than the one in the $y$-direction.
The governing equations in the fixed frame for an incompressible nanofluid can be written as in Akbar and Butt (2014a, 2014b):

\[
\text{div } \vec{V} = 0, \quad (1)
\]

\[
\rho_o \left[ \frac{d\vec{V}}{dt} \right] = -\nabla p + \mu_o \nabla^2 \vec{V} - \sigma B^2 \vec{V}, \quad (2)
\]

\[
(\rho c)_o \left[ \frac{dT}{dt} \right] = -\nabla p + \kappa_o \nabla^2 T + \Phi, \quad (3)
\]

\[
\Phi = \mu_o \left( \left( \frac{\partial \vec{U}}{\partial \vec{R}} \right)^2 + \left( \frac{\partial \vec{W}}{\partial \vec{Z}} \right)^2 \right) + \left( \frac{\partial \vec{U}}{\partial \vec{R}} + \frac{\partial \vec{W}}{\partial \vec{Z}} \right)^2 \quad (4)
\]

where \( \vec{P} \) is the pressure and \( \vec{U}, \vec{W} \) are the respective velocity components in the radial \( \vec{R} \) and axial \( \vec{Z} \) directions, respectively, \( T \) is the temperature, \( \rho \) is the density, \( k \) denotes the thermal conductivity and \( c_p \) is the specific heat at constant pressure. The envelopes of the cilia tips can be expressed mathematically as (Sleigh, 1962; Blake, 1971; Sleigh and Aiello, 1972).

\[
\vec{R} = \vec{R}_0 = \vec{f}(\vec{Z}, \vec{i}) = a + a \varepsilon \cos \left( \frac{2\pi}{\lambda} (\vec{Z} - c \vec{t}) \right), \quad (5)
\]

\[
\vec{Z} = \vec{g}(\vec{Z}, \vec{Z}_0, \vec{i}) = a + a \varepsilon \alpha \sin \left( \frac{2\pi}{\lambda} (\vec{Z} - c \vec{t}) \right), \quad (6)
\]

where \( a \) denotes the mean radius of the tube, \( \varepsilon \) is the non-dimensional measure with respect to the cilia length and \( \lambda \) and \( c \) are the wavelength and wave speed of the metachronal wave, respectively. \( \vec{Z}_0 \) is the reference position of the particle and \( \alpha \) is the measure of the eccentricity of the elliptical motion. If no slip condition is applied, then the velocities of the transporting fluid are just those caused by the cilia tips, which can be given as:

\[
\vec{W} = \frac{\partial \vec{Z}}{\partial t} \bigg|_{\vec{Z}_0} = \frac{\partial \vec{g}}{\partial t} + \frac{\partial \vec{g}}{\partial \vec{Z}} \frac{\partial \vec{Z}}{\partial t} = \frac{\partial \vec{g}}{\partial \vec{R}} + \frac{\partial \vec{g}}{\partial \vec{W}} \vec{W}, \quad (7)
\]

\[
\vec{U} = \frac{\partial \vec{R}}{\partial t} \bigg|_{\vec{Z}_0} = \frac{\partial \vec{f}}{\partial t} + \frac{\partial \vec{f}}{\partial \vec{Z}} \frac{\partial \vec{Z}}{\partial t} = \frac{\partial \vec{f}}{\partial \vec{R}} + \frac{\partial \vec{f}}{\partial \vec{W}} \vec{W}. \quad (8)
\]

If we apply equations (6) and (7) in equations (8) and (9), we obtain:

\[
\vec{W} = \frac{-2\pi}{\varepsilon \alpha \cos \left( \frac{2\pi}{\lambda} (\vec{Z} - c \vec{t}) \right)} \quad (9)
\]

\[
\vec{U} = \frac{2\pi}{\varepsilon \alpha \sin \left( \frac{2\pi}{\lambda} (\vec{Z} - c \vec{t}) \right)} \quad (10)
\]
In the fixed coordinates $(\tilde{R}, \tilde{Z})$, the flow between the two tubes is unsteady. It becomes steady in a wave frame $(\tilde{r}, \tilde{\tau})$ moving with the same speed as the wave moves in the $\tilde{Z}$-direction. The transformations between the two frames are
\[
\tilde{r} = \tilde{R}, \quad \tilde{\tau} = \tilde{Z} - c\tilde{t}, \quad \tilde{u} = \overline{U},
\]
\[
\tilde{w} = \tilde{W} - c, \quad \tilde{p}(\tilde{z}, \tilde{r}, \tilde{\tau}) = \overline{p}(\tilde{Z}, \tilde{R}, \tilde{T}).
\tag{11}
\]

We introduce the following non-dimensional variables:
\[
\begin{align*}
    r &= \frac{\tilde{r}}{a}, \quad z = \frac{\tilde{z}}{\lambda}, \quad w = \frac{\tilde{w}}{c}, \quad u = \frac{\lambda}{ac} \overline{u}, \quad p = \frac{\lambda}{c\mu} \overline{p}, \quad \delta = \frac{a}{\lambda}, \\
    \theta &= \left(\frac{\overline{T} - \overline{T}_0}{\overline{T}_0}\right), \quad t = \frac{c}{\lambda} \overline{t}, \quad M^2 = \frac{\sigma B_r^2 a^2}{\mu_j}, \quad B_r = Ec Pr, \quad h = \frac{\overline{h}}{a}
\end{align*}
\tag{12}
\]

where Re, Pr, B, are the Reynolds, Prandtl and Brinkman number, respectively. With the help of equations (11) and (12), equations (1)–(4) under the assumptions of long wavelength and low Reynolds number approximation take the form:
\[
\frac{\partial \rho}{\partial r} = 0, \tag{13}
\]
\[
\frac{dp}{dz} = \left[\left(\frac{\mu_{\rho}}{\mu_j}\right) \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) - M (w+1) \right], \tag{14}
\]
\[
\left\{ \begin{array}{l}
    k_{sf} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \theta}{\partial r} \right) + Br \left( \frac{\mu_{\rho}}{\mu_j} \right) \left( \frac{\partial w}{\partial r} \right)^2 = 0. \\
    k_j \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) + w \left( \frac{\partial \theta}{\partial r} \right) = 0.
\end{array} \right. \tag{15}
\]

The non-dimensionless boundary conditions:
\[
\frac{\partial w}{\partial r} = 0, \quad \frac{\partial \theta}{\partial r} = 0, \quad \text{at} \quad r = 0,
\]
\[
w = \frac{-2\pi \alpha \beta \cos(2\pi z)}{1 - 2\pi \alpha \beta \cos(2\pi z)}, \quad \theta = 0, \quad \text{at} \quad r = h + \varepsilon \cos(2\pi z), \tag{16}
\]
where $\beta$ is the wave number.

\[
\begin{align*}
    \rho_{sf} &= (1-\varphi) \rho_j + \varphi \rho_j, \quad \mu_{sf} = \frac{\mu_j}{(1-\varphi)^{2/3}}, \\
    (\rho c_p)_{sf} &= (1-\varphi)(\rho c_p)_j + \varphi (\rho c_p)_j, \quad \alpha_{sf} = \frac{k_{sf}}{(\rho c_p)_{sf}}, \\
    k_{sf} &= k_j \left( \frac{k_s + 2k_j - 2\varphi (k_j-k_s)}{k_s + 2k_j + 2\varphi (k_j-k_s)} \right), \quad (\rho c_p)_{sf}, \quad \alpha_{sf}, \quad k_{sf}, \quad k_j.
\end{align*}
\tag{17}
\]
3 Viscous dissipation and entropy generation

The dimensional viscous dissipation term $\Phi$ can be obtained from equations of motion, i.e., Pakdemirli and Yilbas (2006) and Abu-Nada (2006)

$$\Phi = \mu_w \left[ 2 \left( \frac{\partial \pi}{\partial x} \right)^2 + \left( \frac{\partial \pi}{\partial y} \right)^2 + \left( \frac{\partial \pi}{\partial z} \right)^2 \right].$$

The dimensional volumetric entropy generation is defined as (Pakdemirli and Yilbas, 2006; Abu-Nada, 2006).

$$S_{\text{gen}}^v = \frac{k_w}{\theta_0^2} \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \Phi,$$

Dimensionless form of the entropy generation is given as:

$$N_S = \frac{S_{\text{gen}}^v}{S_G} = \left( \frac{k_w}{k_f} \right) \left( \frac{\partial \theta}{\partial r} \right)^2 + \theta_0 B_e \left( \frac{\mu_w}{\mu_f} \right) \left( \frac{\partial w}{\partial r} \right)^2,$$

where

$$S_G = \frac{k_f T_0^2}{\theta_0^2 d^2}, \quad B_e = \frac{c^2 \mu_f}{k_f T_0}, \quad \theta_0 = \frac{\theta_0}{T_0}.$$

Equation (20) consists of two parts. The first part is the entropy generation owing to finite temperature difference ($N_{S\text{cond}}$) and the second part is the entropy generation owing to viscous effects ($N_{S\text{visc}}$). The Bejan number is defined as (Abu-Nada, 2006):

$$Be = \frac{N_{S\text{cond}}}{N_{S\text{cond}} + N_{S\text{visc}}}.$$

4 Solution of the problem

Exact solution of the problem is evaluated. Velocity of the fluid flow can be written as follows:

$$w(r, z) = I_0 \left( \frac{r t}{M + \frac{M}{\theta_0^2}} \cos(2 \pi z) - \frac{\theta_0}{\theta_0^2} - (M + \frac{M}{\theta_0^2}) \left( \frac{2 \pi \theta_0^2 \cos(2 \pi z) - 1}{M (2 \pi \theta_0^2 \cos(2 \pi z) - 1)} \right) \right),$$

where

$$t = \sqrt{M \left( 1 - \phi^2 \right)^z}.$$
Similarly, the temperature distribution is given as:

\[
\theta(r, z) = -\frac{B_r (\frac{d}{r^2} - 2\pi \alpha \beta (M + \frac{d}{r^2}) \cos(2\pi z))^2}{2 \kappa r^2 (1 - 2\pi \alpha \beta \cos(2\pi z))^2 I_0(h) (ht)^2} \left[ t^2 \left( r^2 I_1(rt)^2 - h^2 I_1(ht)^2 \right) + \right] \left[ h^2 \frac{1}{4} I_0(h) (ht) - h I_0 \left( \frac{1}{4} ht \right) \right],
\]

Flow rate is given by:

\[
F = 2\pi \int_0^{\frac{1}{2}} \rho v dr,
\]

This implies that

\[
\frac{dp}{dz} = \frac{4\pi h M \pi c \beta \cos(2\pi z) I_1(ht) - M t^2 \left( F + \pi h^2 \right) (2\pi \alpha \beta \cos(2\pi z) - 1) I_0(ht)}{\pi h (2\pi \alpha \beta \cos(2\pi z) - 1) (ht I_0(ht) - 2 I_1(ht))},
\]

where the mean flow rate \( Q \) is given as:

\[
Q = F + \frac{1}{2} \left( 1 + \frac{e^2}{2} \right).
\]

Integrating equation (24) over the interval \([0, 1]\), we can find the pressure rise given by the expression:

\[
\Delta P = \int_0^1 \frac{dp}{dz} dz.
\]

5 Results and discussion

A brief graphical analysis of the exact analytical solutions is presented here in this section for better understanding. Figure 2(a) and (b) shows the fluid velocity in the horizontal tube with reference to the increase in the Hartmann number and the flow rate of the fluid flow. We can see that the fluid velocity is maximum at the centre of the tube, minimum at the walls and it increases as we increase the flow rate of the fluid, also the velocity slows down when the Hartmann number is increased, i.e., when the electromagnetic forces increase when compared with the viscous forces, the velocity decreases. We notice that the velocity in case of Cu-water is apparently greater as that of the pure water. This implies that if we increase the amount of copper in the nanofluid, the magnitude of the velocity increases.

The pressure gradient along the tube is represented in Figure 3(a) and (b). Along the tube, pressure gradient has a sinusoidal behaviour. For Cu-water, pressure gradient is lesser when compared with pure water. Also, we see that for fixed values of the other constraints, the pressure gradient falls down as the flow rate and the Hartmann number increase. Pressure rise against the flow rate is plotted in Figure 4(a) and (b). We categorise the behaviour of pressure gradients into two parts, first is the peristaltic pumping region (\( \Delta P > 0 \)) where the pressure increases with an increase in Hartmann
number and measure with respect to cilia length at the walls of the tube, other is the augmented pumping region ($\Delta P > 0$) where the behaviour is reversed. Free pumping region holds at $\Delta P = 0$. Note that the more amount of copper in the base fluid, the higher the variation in the pressure rise and with base fluid as water, where the nanoparticle volume fraction $\phi = 0$, the variation is comparatively less.

Figure 2  Velocity profile $w(r, z)$ against the radial distance (see online version for colours)

![Figure 2](image1.png)

Figure 3  Pressure gradient $dp/dz$ along the tube (see online version for colours)

![Figure 3](image2.png)

In Figure 5(a) and (b), we have graphically shown the effect of Hartmann number and Brinkman number on the heat transfer of the governing fluid. When copper is added to base fluid, the temperature of the fluid naturally increases rapidly. This temperature is directly proportional to the Brinkman number and inversely proportional to the Hartmann number. Maximum temperature is found in the centre of the tube ($r = 0$) and minimum temperature is observed at the walls.
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Figure 4  Pressure rise $\Delta P$ against the flow rate $Q$ (see online version for colours)

![Figure 4](image1.png)

(a) (b)

Figure 5  Temperature profile $\theta(r, z)$ against the radial axis $r$ (see online version for colours)

![Figure 5](image2.png)

(a) (b)

The entropy generation is graphically illustrated in Figure 6(a) and (d) with respect to different physical constraints. We see that the entropy generation is directly proportional to all of the Brinkman number, Hartmann number and flow rate of the working fluid. However, entropy generates more rapidly when the amount of copper is increased in the base fluid. This entropy seems to be greater at the walls of the ciliated tube and lesser at the centre of the tube for Cu-water nanofluid. Because entropy involved a transfer of heat from a thermal reservoir to a system via a virtually reversible energy flow process and near the wall of the ciliated tube owing to cilia, there will be more resistance of the fluid with the wall of the tube so entropy near the walls of the tube is high when compared with the centre of the tube. This behaviour is reversed when we consider the base fluid as pure water because in pure water case there will be less resistance between water and walls of the tube so entropy for pure water case is high at the centre and low at the walls of the tube.
Lastly, we have the ratio of heat transfer irreversibility to total irreversibility owing to heat transfer and fluid friction, known as Bejan number. In Figure 7(a) and (d), we see the effects of significant flow parameters on the Bejan number. It is observed that similar to the entropy generation, Bejan number also increases with an increase in Brinkman number because Brinkman number is related to heat conduction from a wall to a flowing viscous fluid. When we increase Brinkman number, viscous forces are more dominant that rises heat transfer irreversibility to total irreversibility owing to heat transfer and fluid friction so Bejan number rises owing to rise in Brinkman number and for high flow rate of the fluid flow heat transfer irreversibility to total irreversibility owing to heat transfer and fluid friction is definitely high that increases Bejan number. But its behaviour changes with the measure with respect to cilia length. However in case of Hartmann number, the Bejan number increases with an increase in electromagnetic forces near the centre of the tube and decreases near the walls of the tube.
Figure 7  Bejan number $Be$ against the radial distance $r$ (see online version for colours)

6 Conclusion

Entropy generation analysis of a Cu-water nanofluid is studied in the presence of heat transfer. The following are the key points of the paper:

- it is noted that both velocity and temperature are maximum at the centre of the tube and minimum near the walls where the flow is affected by the movement of cilia
- if we add the amount of copper in the base fluid, the magnitude of velocity increases and the temperature rises
- entropy generates rapidly in Cu-water nanofluid when compared with the pure water
- near the walls, entropy generation increases for Cu-water nanofluid, but it decreases for pure water.
References


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**Nomenclature**

\( a \) Radius of the tube

\( c \) Wave speed

\( u \) Velocity in the \( r \) direction

\( \rho_{nf} \) Effective density
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>((\rho S)_n)</td>
<td>Heat capacitance</td>
</tr>
<tr>
<td>(k_{nf})</td>
<td>Effective thermal conductivity of the nanofluid</td>
</tr>
<tr>
<td>(M)</td>
<td>Hartmann number</td>
</tr>
<tr>
<td>(\varphi)</td>
<td>Nanoparticle fraction</td>
</tr>
<tr>
<td>(Q)</td>
<td>Flow rate</td>
</tr>
<tr>
<td>(S_{gi})</td>
<td>Entropy generation</td>
</tr>
<tr>
<td>(\bar{T})</td>
<td>Local temperature of the fluid</td>
</tr>
<tr>
<td>(N_{gi})</td>
<td>Entropy generation number</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Wavelength</td>
</tr>
<tr>
<td>(w)</td>
<td>Velocity in the (z) direction</td>
</tr>
<tr>
<td>(\mu_{nf})</td>
<td>Effective dynamic viscosity</td>
</tr>
<tr>
<td>(\alpha_{nf})</td>
<td>Effective thermal diffusivity</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Temperature</td>
</tr>
<tr>
<td>(Br)</td>
<td>Brinkmann number</td>
</tr>
<tr>
<td>(P)</td>
<td>Pressure</td>
</tr>
<tr>
<td>(h)</td>
<td>Height of the tube</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Cilia length</td>
</tr>
<tr>
<td>(Be)</td>
<td>Bejan number</td>
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