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EFFECT OF PERISTALSIS ON DISPERSION IN A CHEMICALLY REACTIVE JEFFREY FLUID FLOW WITH WALL PROPERTIES

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Abstract

The hydrodynamic diffusion of a solute matter in the peristaltic flow of a chemically reactive incompressible Jeffrey fluid is studied as a model of fluid transport in the human intestinal system with wall properties. The long wavelength approximation, Taylor's limiting condition and dynamic boundary conditions at the flexible walls are used to obtain the average effective dispersion coefficient in the presence of combined homogeneous and heterogeneous chemical reactions. The effects of various pertinent parameters on the effective dispersion coefficient are discussed. It is observed that average effective dispersion coefficient increases with amplitude ratio which implies that dispersion is more in the presence of peristalsis. Further, it also increases with the Jeffrey parameter and wall parameters. Conversely, dispersion is found to decreases with homogeneous and heterogeneous chemical reaction rates.

1. Introduction

Dispersion describes the spread of particles through random motion from regions of higher concentration to regions of lower concentration. It is known to balance material in bio-artificial kidney and transporting of oxygen in the human body. The fluid mechanical aspects of hydrodynamic dispersion of a solute in a viscous fluid have received the attention of several investigators (Taylor [1], Padma and Ramana Rao [2], Gupta and Gupta [3]). Subsequently, Chandra and Agarwal [4], Philip and Chandra [5], Alemayehu and Radhakrishnamacharya [6, 7] extended the analysis of Taylor [1] to non-Newtonian fluids.

Peristalsis is an inherent property of many tubular organs of the human body. It arises because of progressive waves propagating along the length of a distensible tube containing fluid. In general, a peristaltic pump is a device for pumping fluids by means of a contraction wave traveling along a tube-like structure. In view of its importance, a number of researchers investigated peristaltic transport of Newtonian and non-Newtonian fluids under different conditions (Fung [8], Shapiro et al. [9], Takagi and Balmforth [10], Radhakrishnamacharya [11], Noreen sher et al. [12], Sankad et al. [13] etc.).

One non-Newtonian fluid model that received considerable attention in the recent past is the Jeffrey fluid, which appears to be an appropriate model to describe some physiological and industrial fluids. This model is a relatively simple linear model which uses time derivatives instead of convective derivatives and it accounts for rheological effects of a visco-elastic fluid (Hayat et al. [14]). Further, Jeffrey fluid model is significant because Newtonian fluid model can be deduced from this as a special case (Vajravelu et al. [15], Pandey and Tripathi [16] and Kothandapani and Srinivas [17]).

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2. **Mathematical Model**

Consider the hydrodynamic diffusion of a solute in peristaltic flow of a Jeffrey fluid in an infinite uniform channel of width 2d. The walls of the channel are flexible and are taken as stretched membrane, on which traveling sinusoidal waves of long wavelength are imposed. Cartesian coordinate system (x, y) is chosen with x-axis aligned with the center line of the channel. The traveling waves are represented by

$$y = \pm h = \pm \left[d + a \sin \frac{2\pi}{\lambda} (x - ct) \right] \tag{1}$$

where a is the amplitude, c is the speed and λ is the wavelength of the peristaltic wave (Fig. 1).

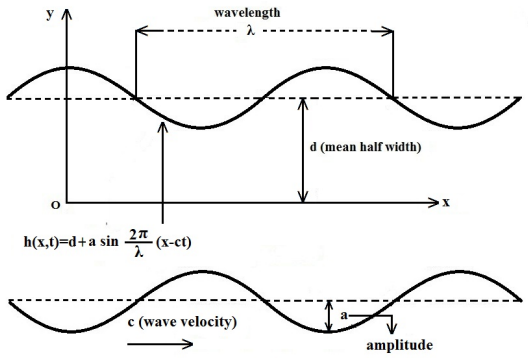


FIGURE 1. An idealized intestinal geometry.

The governing equation of motion of the flexible wall may be expressed as (Mittra and Prasad [18])

$$L(h) = p - p_0 \tag{2}$$

where L is an operator which is used to represent the motion of a stretched membrane with damping forces such that

$$L = -T \frac{\partial^2}{\partial x^2} + m \frac{\partial^2}{\partial t^2} + \mathtt{C} \frac{\partial}{\partial t} \tag{3}$$

Here T is the tension in the membrane, m is the mass per unit area and $\mathtt{C}$ is the coefficient of viscous damping force.
This approach studies the deformability of the conduit wall allowing for fluid-structure interaction in the peristaltic flow.

The equations governing two-dimensional motion of an incompressible Jeffrey fluid for the present problem are given by (Kothandapani and Srinivas [17])

$$\rho \left[\frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} \right] u = -\frac{\partial p}{\partial x} + \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \tag{4}$$

$$\rho \left[\frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} \right] v = -\frac{\partial p}{\partial y} + \frac{\partial S_{yy}}{\partial y} + \frac{\partial S_{yx}}{\partial x} \tag{5}$$

and the equation of continuity is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{6}$$

where u, v are the velocity components in the x and y directions respectively, p is the pressure, ρ is the density, S_{xx}, S_{xy}, S_{yx}, S_{yy} are extra stress components and μ is the viscosity

coefficient.

Under long wavelength approximation , the governing equations for the present problem reduce to,

$$\frac{\partial p}{\partial x} = \frac{\mu}{1+\lambda_1}\frac{\partial^2 u}{\partial y^2} \tag{7}$$

$$\frac{\partial p}{\partial y} = 0 \tag{8}$$

$$\text{and} \quad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{9}$$

It is assumed that $p_0 = 0$ and the channel walls are inextensible so that only lateral motion takes place and the horizontal displacement of the wall is zero.

The no-slip boundary conditions for the velocity is given by

$$u = 0 \quad \text{at} \quad y = \pm h \tag{10}$$

The dynamic boundary conditions at the flexible walls (Mittra and Prasad [18]) can be written as

$$\frac{\partial}{\partial x}L(h) = \left(\frac{\mu}{1+\lambda_1}\right)\frac{\partial^2 u}{\partial y^2} \quad \text{at} \quad y = \pm h \tag{11}$$

where

$$\frac{\partial}{\partial x}L(h) = \frac{\partial p}{\partial x} = -T\frac{\partial^3 h}{\partial x^3} + m\frac{\partial^3 h}{\partial x \partial t^2} + \mathtt{C}\frac{\partial^2 h}{\partial x \partial t}$$

Solving equations (7) to (8) under the boundary conditions (10) and (11), we get

$$u(y) = -\left(\frac{1+\lambda_1}{\mu}\right)\left[\frac{P'}{2}\left(h^2 - y^2\right)\right] \tag{12}$$

where

$$P' = -T\frac{\partial^3 h}{\partial x^3} + m\frac{\partial^3 h}{\partial x \partial t^2} + \mathtt{C}\frac{\partial^2 h}{\partial x \partial t} \tag{13}$$

Further, the mean velocity is defined as

$$\bar{u} = \frac{1}{2h}\int_{-h}^{h} u(y)dy \tag{14}$$

Substituting equation (12) in equation (14), we get

$$\bar{u} = -\left(\frac{1+\lambda_1}{\mu}\right)P'\frac{h^2}{3} \tag{15}$$

If we now consider convection across a plane moving with the mean speed of the flow, then relative to this plane, the fluid velocity is given by (Gupta and Gupta [3])

$$u_x = u - \bar{u} \tag{16}$$

Substituting equations (12) and (15) in equation (16), we get

$$u_x = -\frac{1}{2}\left(\frac{1+\lambda_1}{\mu}\right)P'\left[\frac{h^2}{3} - y^2\right] \tag{17}$$

Diffusion with Combined Homogeneous and Heterogeneous Chemical Reactions

The equation for the concentration C of the solute that diffuses and simultaneously undergoes a first order irreversible chemical reaction in peristaltic transport of a Jeffrey fluid in a channel under isothermal conditions, is given by (Gupta and Gupta [3])

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial y^2} - k_1 C \tag{18}$$

where D is the molecular diffusion coefficient and k_1 is the first order reaction rate constant.

For typical values of physiologically relevant parameters of this problem, it is realized that $\bar{u} = c$ (Alemayehu and Radhakrishnamacharya [6, 7]). Using this condition and making use of the following dimensionless quantities,

$$\theta = \frac{t}{\bar{t}}, \quad \bar{t} = \frac{\lambda}{\bar{u}}, \quad \eta = \frac{y}{d}, \quad \xi = \frac{(x-\bar{u}t)}{\lambda}, \quad H = \frac{h}{d}, \quad P = \frac{d^2}{\mu c}P' \tag{19}$$

equations (17) and (18) reduce to

$$u_x = -\frac{d^2}{2\mu}(1+\lambda_1)P\left[\frac{H^2}{3} - \eta^2\right] \tag{20}$$

$$\frac{\partial^2 C}{\partial \eta^2} - \frac{k_1 d^2}{D}C = \frac{d^2}{\lambda D}u_x\frac{\partial C}{\partial \xi} \tag{21}$$

where

(22)

$P = -\epsilon\left[(E_1+E_2)(2\pi)^3\cos(2\pi\xi) - E_3(2\pi)^2\sin(2\pi\xi)\right]$, $\epsilon\left(=\frac{a}{d}\right)$ is the amplitude ratio, $E_1\left(=-\frac{Td^3}{\lambda^3\mu c}\right)$ is the rigidity, $E_2 = \left(\frac{mcd^3}{\lambda^3\mu}\right)$ is the stiffness and $E_3 = \left(\frac{\mathfrak{C}d^3}{\mu\lambda^2}\right)$ is the viscous damping force in the wall

Following Philip and Chandra [5], the corresponding boundary conditions at the walls in non dimensional form are given by

$$\frac{\partial C}{\partial \eta} + \beta C = 0 \quad \text{at} \quad \eta = H = [1+\epsilon\sin(2\pi\xi)] \tag{23}$$

$$\frac{\partial C}{\partial \eta} - \beta C = 0 \quad \text{at} \quad \eta = -H = -[1+\epsilon\sin(2\pi\xi)] \tag{24}$$

where $\beta = fd$ is the heterogeneous reaction rate parameter corresponding to catalytic reaction at the walls.

Solving equation (21) under the boundary conditions (23) and (24) by assuming $\partial C/\partial\xi$ is independent of η at any cross section, we get the solution for the concentration of the solute C as

(25)

$$C(\eta) = \left[\frac{d^4}{2\lambda\mu D}\frac{\partial C}{\partial \xi}\right]\frac{P}{\alpha^2}(1+\lambda_1)\left[\frac{\cosh(\alpha\eta)}{L}\left(2H + \beta\left(\frac{2H^2}{3}+\frac{2}{\alpha^2}\right)\right) - \left(\eta^2 - \frac{H^2}{3} + \frac{2}{\alpha^2}\right)\right]$$

where $L = \alpha\sinh(\alpha H) + \beta\cosh(\alpha H)$ and $\alpha^2 = k_1 d^2/D$.

The volumetric rate Q at which the solute is transported across a section of the channel of unit breadth is defined by

$$Q = \int_{-H}^{H} Cu_x d\eta \tag{26}$$

Substituting equations (20) and (25) in equation (26), we get the volumetric rate Q as

$$Q = -2\frac{d^6}{\lambda\mu^2 D}\frac{\partial C}{\partial \xi}G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3, \lambda_1) \tag{27}$$

where

$$G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3, \lambda_1) = \frac{(1+\lambda_1)^2}{\alpha^2}\Big[\Big(\frac{P}{3L\alpha^3}\Big)\big(H + \frac{\beta H^2}{3} + \frac{\beta}{\alpha^2}\big)\big(3\alpha H\cosh(\alpha H) - (3 + H^2\alpha^2)\sinh(\alpha H)\big) + \frac{PH^5}{45}\Big] \tag{28}$$

Now comparing the equation (27) with Fick's first law of diffusion, the effective dispersion coefficient D^* with which the solute disperses relative to a plane moving with the mean speed of the flow, is obtained as,

$$D^* = 2\frac{d^6}{\mu^2 D}G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3, \lambda_1) \tag{29}$$

Let the average of G be $\bar{G}$, and is defined by

$$\bar{G} = \int_0^1 G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3, \lambda_1)d\xi \tag{30}$$

3. Numerical Results and Discussion

The equation (30) gives the dispersion coefficient D^* through the function $\bar{G}$, which has been computed numerically using MATHEMATICA software and the results are presented graphically. The dimensionless quantities involved in the discussion are: the amplitude ratio ϵ, the homogeneous reaction rate α, the heterogeneous reaction rate β, the Jeffrey parameter λ_1 and the wall parameters E_1, E_2, E_3.

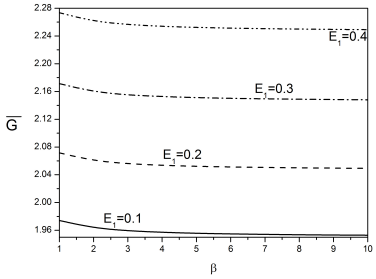


FIGURE 2. Effect of E_1 on $\bar{G}$ ($\epsilon = 0.2$, $\alpha = 0.5$, $E_2 = 0.0$, $E_3 = 0.0$, $\lambda_1 = 1$)

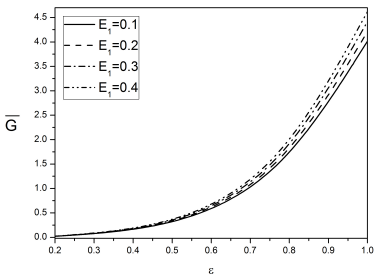


FIGURE 3. Effect of E_1 on $\bar{G}$ ($\beta = 5$, $\alpha = 0.5$, $E_2 = 4.0$, $E_3 = 0.0$, $\lambda_1 = 1$)

The effect of the rigidity parameter (E_1) on the effective dispersion coefficient is shown in Figs. 2 - 4. It is observed that the dispersion increases with the rigidity parameter in the cases of (i) no stiffness in the wall ($E_2 = 0$) and perfectly elastic channel wall ($E_3 = 0$) (Fig. 2); (ii) stiffness in the wall ($E_2 \neq 0$) and perfectly elastic wall ($E_3 = 0$) (Fig. 3); (iii) no stiffness in the wall ($E_2 = 0$) and dissipative wall ($E_3 \neq 0$) (Fig. 4). For all values of rigidity parameter in the case of (i) i.e. Fig. 2, the dispersion coefficient decreases as the heterogeneous reaction rate increases from unity to 10. Fig. 3 shows that dispersion coefficient increases with amplitude ratio ϵ . A nonlinear and positive influence of peristalsis on effective dispersion coefficient is therefore evident in Fig. 3. In Fig. 4, dispersion coefficient,

$\bar{G}$ clearly descends as the homogeneous reaction rate α increases, demonstrating an inverse relationship. The rate of descent of the profiles is accentuated with higher values of the rigidity parameter E_1. This clearly demonstrates that both parameters exert a non-trivial effect on hydrodynamic dispersion in peristaltic flow and has implications for the effectiveness of dispersion phenomena.

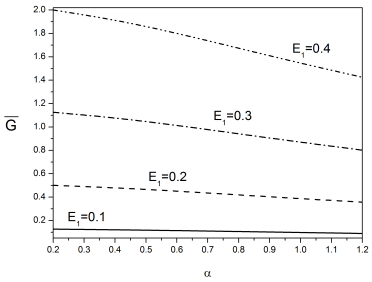


FIGURE 4. Effect of E_1 on $\bar{G}$ ($\beta = 5$, $\epsilon = 0.2$, $E_2 = 0.0$, $E_3 = 0.06$, $\lambda_1 = 1$)

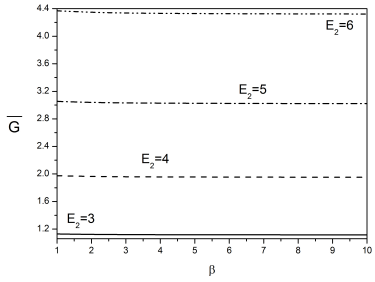


FIGURE 5. Effect of E_2 on $\bar{G}$ ($\epsilon = 0.2$, $\alpha = 0.5$, $E_1 = 0.1$, $E_3 = 0.0$,$\lambda_1 = 1$)

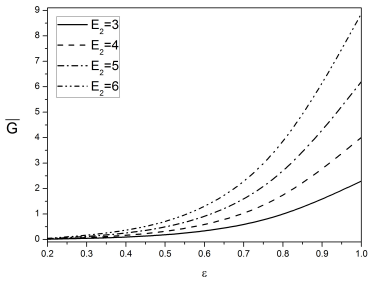


FIGURE 6. Effect of E_2 on $\bar{G}$ ($\beta = 5$, $\alpha = 0.5$, $E_1 = 0.1$, $E_3 = 0.06$, $\lambda_1 = 1$)

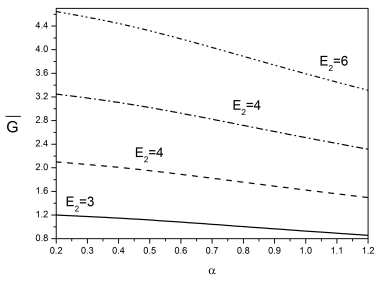


FIGURE 7. Effect of E_2 on $\bar{G}$ ($\beta = 5$, $\epsilon = 0.2$, $E_1 = 0.1$, $E_3 = 0.06$, $\lambda_1 = 1$)

Figs. 5 - 7 show that the dispersion coefficient increases as the stiffness in the wall E_2 increases for both the cases of perfectly elastic wall ($E_3 = 0$) (Fig. 5) and dissipative wall ($E_3 \neq 0$) (Figs. 6 and 7). In Fig. 5, the dispersion coefficient values are plateau-profiles and remain at consistent distances from one another, as the heterogeneous reaction rate β ascends from 1 to 10. The response to a change in amplitude ratio ϵ (Fig. 6) and homogeneous reaction rate α (Fig. 7) is similar to that observed in Figs. 3 and 4. Dispersion coefficient sharply ascends with an increase in the former, whereas it decays approximately linearly with a rise in the latter.

It is seen from Figs. 8 - 10 that the dispersion increases with viscous damping force (E_3) in the cases of (i) stiffness in the wall ($E_2 \neq 0$) (Figs. 8 and 10) and (ii) no stiffness in the wall ($E_2 = 0$) (Fig. 9). Distinct from earlier graphs, it is observed that a sharp monotonic decay in hydrodynamic dispersion coefficient (Fig. 8) accompanies an increase in heterogeneous chemical reaction rate β. It is also observed that the variation of dispersion coefficient with amplitude ratio ϵ (Fig. 9) is similar to that observed in Fig. 6. Further, Fig. 10 indicates that the effect of homogeneous reaction rate α is less pronounced for all values of viscous damping E_3, compared with the distributions in Figs. 4 and 7.

It is noticed that the effective dispersion coefficient $\bar{G}$ increases with Jeffrey parameter λ_1 (Figs. 11 - 13). This is true for the cases of (i) stiffness in the wall ($E_2 \neq 0$) and perfectly

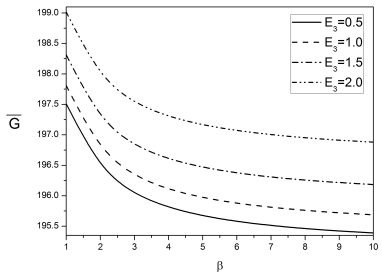


FIGURE 8. Effect of E_3 on $\bar{G}$ ($\alpha = 0.5$, $\epsilon = 0.2$, $E_1 = 0.1$, $E_2 = 4.0$,$\lambda_1 = 1$)

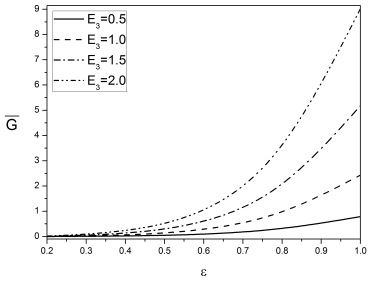


FIGURE 9. Effect of E_3 on $\bar{G}$ ($\beta = 5$, $\alpha = 0.5$, $E_1 = 0.1$, $E_2 = 0.0$, $\lambda_1 = 1$)

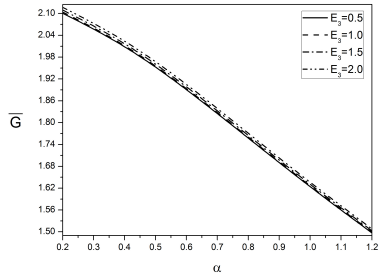


FIGURE 10. Effect of E_3 on $\bar{G}$ ($\beta = 5$, $\epsilon = 0.2$, $E_1 = 0.1$, $E_2 = 4.0$, $\lambda_1 = 1$)

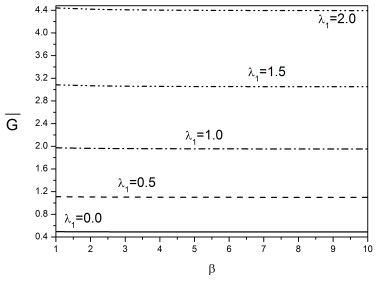


FIGURE 11. Effect of λ_1 on $\bar{G}$ ($\epsilon = 0.2$, $\alpha = 0.5$, $E_1 = 0.1$, $E_2 = 4.0$,$E_3 = 0.0$)

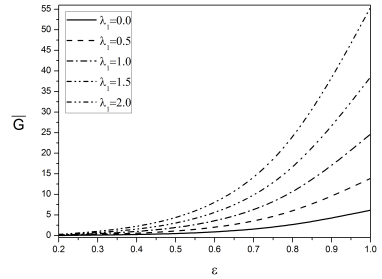


FIGURE 12. Effect of λ_1 on $\bar{G}$ ($\beta = 5$, $\alpha = 0.5$, $E_1 = 0.1$, $E_2 = 0.0$, $E_3 = 0.06$)

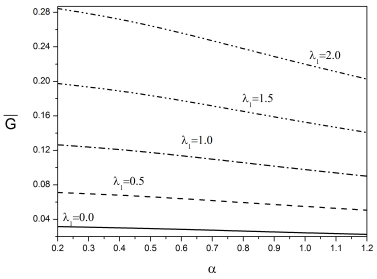


FIGURE 13. Effect of λ_1 on $\bar{G}$($\epsilon = 0.2$, $\alpha = 0.5$, $E_1 = 0.1$, $E_2 = 0.0$, $E_3 = 0.06$)

elastic wall ($E_3 = 0$) (Fig. 11); (ii) no stiffness in the wall ($E_2 = 0$) and dissipative wall ($E_3 \neq 0$) (Figs. 12 and 13). It is also noticed that the hydrodynamic dispersion values are largely invariant with alteration in the heterogeneous chemical reaction rate β (Fig. 11).

It is seen from Figs. 3, 6, 9 and 12 that the average effective dispersion coefficient increases with amplitude ratio ϵ. This implies that the peristalsis enhances dispersion of a solute in fluid flow. This result agrees with that of Alemayehu and Radhakrishnamacharya [8, 9]. Further, as discussed earlier, the hydrodynamic dispersion decreases with homogeneous chemical reaction rate (Figs. 4, 7, 10 and 13) and heterogeneous chemical reaction rate (Figs. 2, 5, 8 and 11). This result agrees with that of Padma and Ramana Rao [2], Gupta and Gupta [3].

4. **Conclusion**

The effect of combined homogeneous and heterogeneous chemical reactions on dispersion in peristaltic flow of a Jeffrey fluid with wall properties has been studied analytically under long wavelength approximation and Taylor's limiting condition. The model developed is relevant to fluid transport in the human digestive system. It is observed that peristaltic motion enhances hydrodynamic dispersion and dispersion decreases with both the homogeneous and heterogeneous chemical reaction rates. It is also observed that the effective dispersion coefficient increases with Jeffrey parameter, rigidity, stiffness, viscous damping.

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