PULSATIC FLOW OF FLUID IN A FLAT CHANNEL WITH CONDUCTOR WALL

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Abstract. *The paper deals with the problem of pulsating flow of an incompressible viscous fluid in a permeable-walled flat channel. In this case, the length of the flat channel is considered to be large enough. That is, the ratio of channel width to channel length is small enough, the ratio of transverse velocity to longitudinal velocity, and the Reynolds number are also sufficiently small that the Nave-Stokes equation dashed and the necessary boundary conditions are formed. As a result of solving the problem, appropriate formulas were obtained and analyzes were performed. Based on the results of the analysis, it is shown that the pulse wave propagation velocity at sufficiently small values of the oscillation frequency parameter is determined by the formula* $c_0 = 5\sqrt{\frac{\nu^2}{h^2\gamma^*}}$ *- formula, and this formula is accepted as the base pulse wave propagation velocity. It was shown that the pulse wave propagation velocity did not differ significantly from the base pulse wave propagation velocity at small values of the oscillation frequency parameter, and that the pulse wave propagation velocity at its large values differed significantly from its base velocity. In addition, the attenuation of the pulse wave depending on the oscillation frequency parameter was analyzed, it was found that at low values of the oscillation frequency parameter the attenuation of the wave is almost non-existent, and at its large values the attenuation rate increases significantly.*

Keywords: *kinematic viscosity coefficient, Nave-Stokes equation, pressure, Poiseuille stream, boundary condition, conductivity coefficient, vibration frequency.*

ПУЛЬСИРУЮЩЕЕ ТЕЧЕНИЕ ЖИДКОСТИ В ПЛОСКОМ КАНАЛЕ С ПРОВОДЯЩЕЙ СТЕНКОЙ

Аннотация. *В работе рассматривается задача о пульсирующем течении несжимаемой вязкой жидкости в плоском канале с проницаемыми стенками. При этом длина плоского канала считается достаточно большой. То есть отношение ширины канала к длине канала достаточно мало, отношение поперечной скорости к продольной скорости и число Рейнольдса также достаточно малы, чтобы уравнение Нава-Стокса стало штриховым и сформировались необходимые граничные условия. В результате решения задачи были получены соответствующие формулы и проведены анализы. По результатам анализа показано, что скорость распространения пульсовой волны при достаточно малых значениях параметра частоты колебаний определяется по формуле* $c_0 = 5\sqrt{\frac{\nu^2}{h^2\gamma^*}}$ *- формула, и эта формула принимается за базовую скорость распространения пульсовой волны. Показано, что скорость распространения пульсовой волны существенно не отличается от базовой скорости распространения пульсовой волны при малых значениях параметра частоты колебаний, а скорость распространения* *пульсовой волны при ее больших значениях существенно отличается от ее базовой скорости. Кроме того, проанализировано затухание пульсовой волны в зависимости от параметра частоты колебаний, установлено, что при малых значениях параметра частоты колебаний затухание волны практически отсутствует, а при больших его значениях скорость затухания увеличивается. существенно.*

Ключевые слова: *коэффициент кинематической вязкости, уравнение Нава-Стокса, давление, поток Пуазейля, граничное условие, коэффициент проводимости, частота колебаний.*

INTRODUCTION

Theoretical studies [1-5,10-23] have shown that solving problems about the pulsating flow of viscous fluid in conductive-walled flat channels leads to serious mathematical difficulties. Therefore, simplification methods are used to solve such problems, or the problem [5-9] is solved on the basis of average velocities along the channel section. This paper discusses specific issues about the pulsating flow of viscous liquids in conductive-walled flat channels. The main purpose is to study the motion of viscous fluids on the basis of simplified mathematical modeling and compare the results with the hydrodynamic laws of fluid flow in flat channels, especially in impermeable walls, and, consequently, to identify new hydrodynamic effects. It is known that stationary oscillating (pulsating) currents, in which the transition processes in the flow of liquids do not occur, are of particular interest in science, engineering and technological processes. In such processes, even if the motion of the fluid occurs in a stationary mode, due to the presence of oscillating motion, the process under consideration is a periodic function of time. In this case, it is assumed that the oscillations of the fluid occur in the same state in each period. Therefore, in solving problems related to fluid flow, it is possible to use the periodic functions of time, which makes it much easier to solve a system of differential equations. Numerous scientific and practical researches have been devoted to the pulsating currents in flat-walled flat channels and cylindrical pipes by domestic and foreign scientists. In particular [7-11], nonstationary, stationary oscillating currents of pulsating viscous fluids in channels and tubes have been sufficiently investigated. Womersley [22–27] was the first to apply scientific research to the flow of pulsating viscous fluids in the circulatory system of biomechanics. In this case, blood is considered as a Newtonian fluid, and its flow is characterized by the formation of a pressure gradient under the influence of a function expressed in sinusoidal and general form using the Fure series. Although the cases of pulsating currents in ducts and pipes considered to be Newtonian fluids [1,2,5,9,10,20,21] have been sufficiently studied, very little research has been devoted to the fluxes of viscous fluids in permeable wall ducts and tubes in this area [11-19]. Therefore, in this paper, the pulsating flows of viscous liquids in conductive-walled flat channels are considered. The result is compared with the laws of pulsating flow in the existing impermeable wall channels and the required hydrodynamic effects are obtained.

MATERIALS AND METHODS

In this paper, the pulsating currents of viscous liquids in conductive-walled flat channels are considered for a case where the channel length is large enough. In this case, the ratio of channel width to channel length is considered small enough, the ratio of transverse velocity to longitudinal velocity, and the Reynolds number are also considered small enough. Given these conditions, the Nave-Stokes equation [3,4,6-8] is linearized by moving from the old variables to the new variables and without taking into account the limits involving small parameters in the system of equations, and it looks like this:

$$\begin{cases} \frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial y^2}, \\ \frac{\partial p}{\partial y} = 0, \ \frac{\partial u}{\partial x} + \frac{\partial \vartheta}{\partial y} = 0 \end{cases} \tag{1}$$

Here u, ϑ - longitudinal and transverse velocities, respectively; ρ - fluid density; p - pressure x, y -appropriate longitudinal and transverse coordinate axes; t -time; ν -kinematic viscosity coefficient.

It is known that in stationary oscillating (pulsating) currents in which no transition processes occur in the flow of liquids, even if the oscillations occur in a steady state, the process under consideration consists of a periodic function of time. In this case, it is assumed that the oscillations of the fluid occur in the same state in each period. Therefore, in solving problems related to fluid flow, it is possible to use periodic functions of time, which makes it much easier to solve a system of differential equations. Therefore, since we consider the flow under the influence of the pressure gradient here, the pressure gradient can be obtained by the function in this view

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = (-\frac{1}{\rho}\frac{\partial \overline{p}_0(x)}{\partial x}) + (-\frac{1}{\rho}\frac{\partial \overline{p}_1(x)}{\partial x}) cos\omega t) \tag{2}$$

here

$$-\frac{1}{\rho}\frac{\partial p_0}{\partial x} = (-\frac{1}{\rho}\frac{\partial \overline{p}_0(x)}{\partial x}) \tag{3}$$

is the pressure gradient that forms the steady flow

$$-\frac{1}{\rho}\frac{\partial p_1}{\partial x} = (-\frac{1}{\rho}\frac{\partial \overline{p}_1(x)}{\partial x}) e^{i\omega t} \tag{4}$$

It is the pressure gradient that creates the oscillating (pulsating) flow.

Since the change in pressure gradient is expressed by a complex function, other quantities that characterize the flow are also expressed in terms of a complex function.

$$u = u_0 + u_1 e^{i\omega t}, \ \vartheta = \vartheta_0 + \vartheta_1 e^{i\omega t}, \ \ p = p_0 + p_1 e^{i\omega t}, \ Q = Q_0 + Q_1 e^{i\omega t} \tag{5}$$

Substituting these quantities (5), (4) and (3) into the system of equations (1) and equating the expressions before $e^{i\omega t}$, we obtain the following system of equations:

$$\begin{cases} 0 = (-\frac{1}{\rho}\frac{\partial \overline{p}_0}{\partial x}) + \nu\frac{\partial^2 u_0}{\partial y^2}, \\ \frac{\partial \overline{p}_0}{\partial y} = 0, \ \frac{\partial u_0}{\partial x} + \frac{\partial \vartheta_0}{\partial y} = 0 \end{cases} \tag{6}$$

$$\begin{cases} i\omega u_1 = (-\frac{1}{\rho}\frac{\partial \overline{p}_1}{\partial x}) + \nu\frac{\partial^2 u_1}{\partial y^2}, \\ \frac{\partial p_1}{\partial y} = 0, \ \frac{\partial u_1}{\partial x} + \frac{\partial \vartheta_1}{\partial y} = 0 \end{cases} \quad (7)$$

To solve the system of equations (6) and (7) we need to form boundary conditions. Depending on the problem, we define these conditions for the system of equations (6) as follows.

$$\begin{gathered} y = 0, \ \frac{\partial u_0}{\partial y} = 0, \ \vartheta_0 = 0 \\ y = h, \ \ u_0 = 0, \ \ \vartheta_0 = \frac{\gamma^* h}{\mu}(\overline{p}_0 - p_c) \end{gathered} \quad (8)$$

For a similar system of equations (7), we define as follows

$$\begin{gathered} y = 0, \ \frac{\partial u_1}{\partial y} = 0, \ \vartheta_1 = 0 \\ y = h, \ \ u_1 = 0, \ \ \vartheta_1 = \frac{\gamma^* h}{\mu}(\overline{p}_1 - p_c) \end{gathered} \quad (9)$$

It is known that the solution of the system of equations (6) satisfying the boundary condition (8) is given in detail in the work [19], and the analysis of the solutions is also carried out. Therefore, in this paper, we solve the system of equations (7), (9) relating to the pulsating flow of a viscous fluid on the basis of boundary conditions.

$$\frac{\partial^2 u_1}{\partial y^2} - \frac{i\omega u_1}{\nu} = (-\frac{1}{\rho\nu}\frac{\partial \overline{p}_1}{\partial x}) \quad (10)$$

These are fundamental solutions of the homogeneous part of the equation

$$\cos(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) \ \text{ва} \ \sin(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) \quad (11)$$

consisting of functions, the general solution of a genital part is found in the following view:

$$\overline{u}(y) = C_1 \cos(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) + C_2 \sin(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) \quad (12)$$

Since the heterogeneous part of the equation is only a function of the variable *x*, its solution is sought in this view:

$\overline{u}^* = A(x)$, in this case $\frac{\partial^2 \overline{u}^*}{\partial y^2} = 0$, the solution of the non-homogeneous part of equation

(12) will be $\bar{u}^* = \frac{1}{\rho i\omega}(-\frac{\partial \bar{p}_1(x)}{\partial x})$. With this in mind, the overall solution to the problem is determined as follows:

$$\bar{u}(y) = C_1 \cos(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) + C_2 \sin(,i^{\frac{3}{2}}\alpha_0 \frac{y}{h}) + \frac{1}{\rho i\omega}(-\frac{\partial \bar{p}_1(x)}{\partial x}) \quad (13)$$

We find the integral unknown coefficients in solution (13) from the boundary condition (9). (13) It follows that if we take the product of both sides of solution y and make it equal to zero $C_2 = 0$. The coefficient (2) is found from the boundary condition (1).

$$C_1 = -\frac{1}{\rho i\omega}(-\frac{\partial \bar{p}_1(x)}{\partial x})\frac{1}{\cos(i^{\frac{3}{2}}\alpha_0)} \quad (14)$$

By substituting the values of the coefficients C_1 and C_2 into solution (13), we obtain this solution.

$$\bar{u}(x,y) = \frac{1}{\rho i\omega}(-\frac{\partial \bar{p}_1(x)}{\partial x})[1 - \frac{\cos(i^{\frac{3}{2}}\alpha_0 \frac{y}{h})}{\cos(i^{\frac{3}{2}}\alpha_0)}] \quad (15)$$

here $\alpha_0 = \sqrt{\frac{\omega}{\nu}}h, \quad \nu = \frac{\eta}{\rho}$

Substituting the found solutions (15) into (13), we determine the following final solution.

$$u(x,y,t) = \frac{h^2}{2\eta}(-\frac{\partial \bar{p}_1(x)}{\partial x})\left[2real\left[\frac{1}{i\alpha_0^2}\left(1 - \frac{\cos\left(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}\right)}{\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)e^{i\omega t}\right]\right] \quad (16)$$

As a result of dividing the solution (16) formed for the velocity by its maximum velocity in the stationary state, a dimensionless solution of this form is found.

$$\frac{u(x,y,t)}{<u_0>} = 3(-\frac{\partial \bar{p}_1}{\partial x})real\left[\frac{1}{i\alpha_0^2}\left(1 - \frac{\cos\left(i^{\frac{3}{2}}\alpha_0 \frac{y}{h}\right)}{\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)e^{i\omega t}\right] \quad (17)$$

here $<u_0> = \frac{1}{3\eta}\left(-\frac{\partial p(x)}{\partial x}\right)_0 h^2$ - the maximum velocity of the stationary flow in which the wall of the Newtonian fluid is impermeable;

$(-\frac{\partial p_1}{\partial x})/(-\frac{\partial p}{\partial x})_0 = -\frac{\partial \bar{p}_1}{\partial x}$. Integrating both sides of formula (17) for velocity distribution from (1) to (2) and dividing it by (3), we obtain the following formula for the average velocity of a liquid.

$$<\bar{u}(x,t)>=\frac{<u(x,t)>}{<u_0>}=(-\frac{\partial \bar{p}_1}{\partial x})real\left[\frac{3}{i\alpha_0^2}\left(1-\frac{\sin\left(i^{\frac{3}{2}}\alpha_0\right)}{\left(i^{\frac{3}{2}}\alpha_0\right)\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)e^{i\omega t}\right] \quad (18)$$

here $<u_0>=\frac{1}{3\eta}\left(-\frac{\partial p}{\partial x}\right)_0 h^2$ -average longitudinal velocity in a stationary Poiseuille flow.

Now that the flat channel wall is permeable using these found formulas, the pressure gradient here and the average velocity will be variable along the longitudinal axis. Therefore, using the boundary condition and using the relationships between the average velocity and the pressure gradient through the formulas found, we construct the following system of equations to determine their changes along the longitudinal axis.

$$\begin{cases}\frac{\partial \bar{p}(x)}{\partial x}=-z<\bar{u}(x)>,\\ \frac{\partial<\bar{u}(x)>}{\partial x}=-k\bar{p}(x)\end{cases} \quad (19)$$

here $k=\frac{\gamma^*}{\eta}$, $z=\frac{3\eta}{h^2}\bar{z}$

$$\bar{z}=\left[\frac{3}{i\alpha_0^2}\left(1-\frac{\sin\left(i^{\frac{3}{2}}\alpha_0\right)}{\left(i^{\frac{3}{2}}\alpha_0\right)\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)\right]^{-1}$$

Differentiating the first equation of the system of equations (19) on the variable x, we obtain this equation by substituting its value in the second equation $\frac{\partial<u(x)>}{\partial x}$.

$$\frac{\partial^2\bar{p}(x)}{\partial x^2}-\bar{k}\bar{z}\,\bar{p}(x)=0,\quad \bar{k}=\frac{3\gamma^*}{h^2}. \quad (20)$$

The boundary condition for this equation is as follows

$$\bar{p}=\sum_{n=1}^{N}\bar{p}_1^0 \text{ at } x=0,$$

$$\bar{p}=\sum_{n=1}^{N}\bar{p}_1^L \text{ at } x=L. \quad (21)$$

In this case, the solution of equation (20) (21) is given by the boundary condition as follows.

$$\overline{p}(x)=\overline{p}_1^0\frac{sh\sqrt{\overline{k}\,\overline{z}}L\left(1-\frac{x}{L}\right)}{sh\sqrt{\overline{k}\,\overline{z}}L}+\overline{p}_1^L\frac{sh\sqrt{\overline{k}\,\overline{z}}L\frac{x}{L}}{sh\sqrt{\overline{k}\,\overline{z}}L}\Bigg], \tag{22}$$

$$<\overline{u}(x)>=p_1^0\frac{ch\sqrt{\overline{k}\,\overline{z}}L\left(1-\frac{x}{L}\right)}{sh\sqrt{\overline{k}\,\overline{z}}L}-\overline{p}_1^L\frac{sh\sqrt{\overline{k}\,\overline{z}}L\frac{x}{L}}{sh\sqrt{\overline{k}\,\overline{z}}L}\sqrt{\frac{\overline{k}}{\overline{z}}}. \tag{23}$$

To give the results of the calculations using formulas (22) and (23) found, we begin by analyzing the properties of the magnitudes in the argument of the hyperbolic sine and hyperbolic cosine functions. It is known that these magnitudes are one of the main factors of wave propagation, and these arguments can be used to determine the speed of propagation of a pulse wave and its extinction along the longitudinal axis. Below we present the results of the analysis of these quantities.

RESULTS

The formulas found (22) and (23) express the change in pressure and longitudinal velocity along the longitudinal axis, and since these formulas are mainly dependent on the complex parameter $\sqrt{\overline{k}\,\overline{z}}L$, we express it in this view:

$$\sqrt{\overline{k}\,\overline{z}}L=\overline{\chi}+\overline{\beta}i\ . \tag{24}$$

here $$\overline{z}=\left[\frac{3}{i\alpha_0^2}\left(1-\frac{\sin\left(i^{\frac{3}{2}}\alpha_0\right)}{\left(i^{\frac{3}{2}}\alpha_0\right)\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)\right]^{-1},\qquad \overline{k}=\frac{3\gamma^*}{h^2} \tag{25}$$

We distinguish the real and abstract parts of $\overline{z}$ as follows

$$\overline{z}=\left[\frac{3}{i\alpha_0^2}\left(1-\frac{\sin\left(i^{\frac{3}{2}}\alpha_0\right)}{\left(i^{\frac{3}{2}}\alpha_0\right)\cos\left(i^{\frac{3}{2}}\alpha_0\right)}\right)\right]^{-1}=\frac{\overline{R}}{3}+\frac{\overline{L}}{3}i$$

$$\overline{R}=\frac{\alpha_0^2\left(A_1^2+B_1^2\right)}{(A_2^2+B_2^2)}B_2,\qquad \overline{L}=\frac{\left(A_1^2+B_1^2\right)\alpha_0^2}{A_2^2+B_2^2}A_2,$$

here

$$A_1=\overline{A}\overline{M}_1+\overline{B}M_1,\quad B_1=\overline{A}M_1-\overline{B}\overline{M}_1,$$

$$A_2=\left(A_1^2+B_1^2\right)-A_1C-B_1D,\quad B_2=\left(B_1C-A_1D\right)$$

$$C=\sin M_1 ch\overline{M}_1,\quad D=-\cos M_1 sh\overline{M}_1.$$

$$i^{\frac{3}{2}}\alpha_0 = \frac{\alpha_0}{\sqrt{2}}(1-i) = M_1 - \bar{M}_1 i$$

Now we find $\bar{\chi}$, $\bar{\beta}$ by substituting the values of $\bar{z}$ and $\bar{k}$ into the formula

$$\sqrt{\bar{k}\,\bar{z}}L = \bar{\chi} + \bar{\beta}i$$

$$\sqrt{\bar{k}\,\bar{z}}L = L\sqrt{\frac{3\gamma^*}{h^2}}\sqrt{\frac{1}{3}}(\sqrt[4]{\bar{R}^2+\bar{L}^2}(\cos\frac{\varphi}{2} + i\sin\frac{\varphi}{2})) =$$

$$\sqrt{\frac{\gamma^*}{h^2}}L(\sqrt[4]{\bar{R}^2+\bar{L}^2}(\cos\frac{\varphi}{2} + i\sin\frac{\varphi}{2})),\ \varphi = arctg\frac{\bar{L}}{\bar{R}}$$

From this formula we find $\bar{\chi}$, $\bar{\beta}$ accordingly:

$$\bar{\chi} = \sqrt{\frac{\gamma^*}{h^2}}L(\sqrt[4]{\bar{R}^2+\bar{L}^2}\cos\frac{\varphi}{2}) \quad \bar{\beta} = \sqrt{\frac{\gamma^*}{h^2}}L(\sqrt[4]{\bar{R}^2+\bar{L}^2}\sin\frac{\varphi}{2})$$

here $\bar{\chi}$ - the coefficient characterizing the extinction of the wave; $\frac{1}{\bar{\beta}}$ – a coefficient that characterizes the speed of propagation of a pulse wave; $c = \frac{\omega L}{\bar{\beta}}$ - pulse wave propagation velocity; $c_0 = 5\sqrt{\frac{\nu^2}{h^2\gamma^*}}$ - base pulse wave propagation velocity; γ^* – wall conductivity; η – viscous dynamic coefficient of the liquid; ω – vibration frequency; L –pipe length; ρ - density.

From formula $c = \frac{\omega L}{\bar{\beta}}$ we find the velocity of propagation of the pulse wave

$$c = \frac{\omega L}{\bar{\beta}} = \frac{\omega L}{\sqrt{\frac{\gamma^*}{h^2}}L(\sqrt[4]{\bar{R}^2+\bar{L}^2}\sin\frac{\varphi}{2})} = \sqrt{\frac{\nu^2}{h^2\gamma^*}}\alpha_0^2(\sqrt[4]{\bar{R}^2+\bar{L}^2}\sin\frac{\varphi}{2})^{-1}$$

$$\frac{c}{c_\infty} = \alpha_0(\sqrt[4]{\bar{R}^2+\bar{L}^2}\sin\frac{\varphi}{2})^{-1}$$

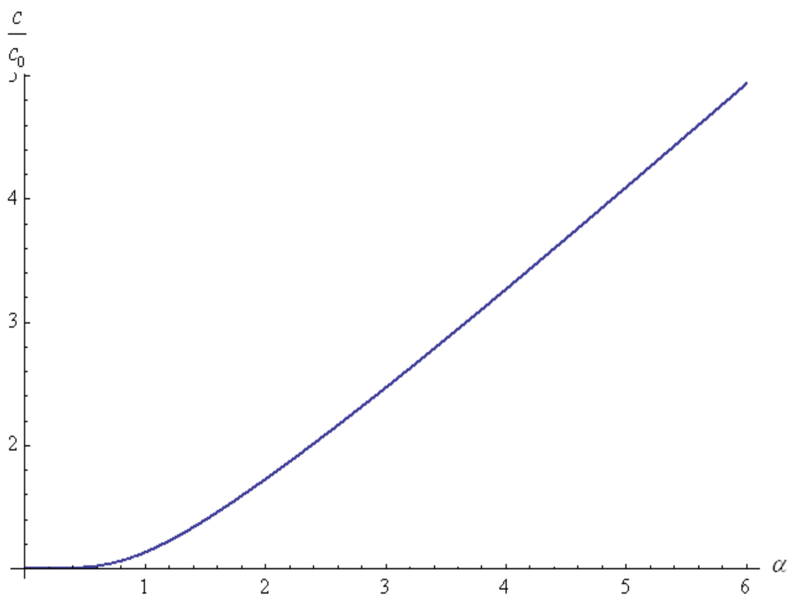
DISCUSSION

Based on the formulas determined as a result of solving the problem, an analysis was performed on the pulse wave propagation velocity, depending on the oscillation frequency parameter.

Figure 1. illustrates the variation of the pulse wave propagation velocity depending on the oscillation frequency parameter. At sufficiently small values of the oscillation frequency parameter, it was found that the pulse wave propagation velocity was expressed by formula

$c_0 = 5\sqrt{\frac{\nu^2}{h^2\gamma^*}}$ and this formula was adopted as the base pulse wave propagation velocity.

Figure 1.



The change in pulse wave propagation velocity depending on the oscillation frequency parameter.

The figure shows that the pulse wave propagation velocity does not differ significantly from the base pulse wave propagation velocity at small values of the oscillation frequency parameter. At large values of the oscillation frequency parameter, it was found that the speed of propagation of the pulse wave differs significantly from its base velocity.

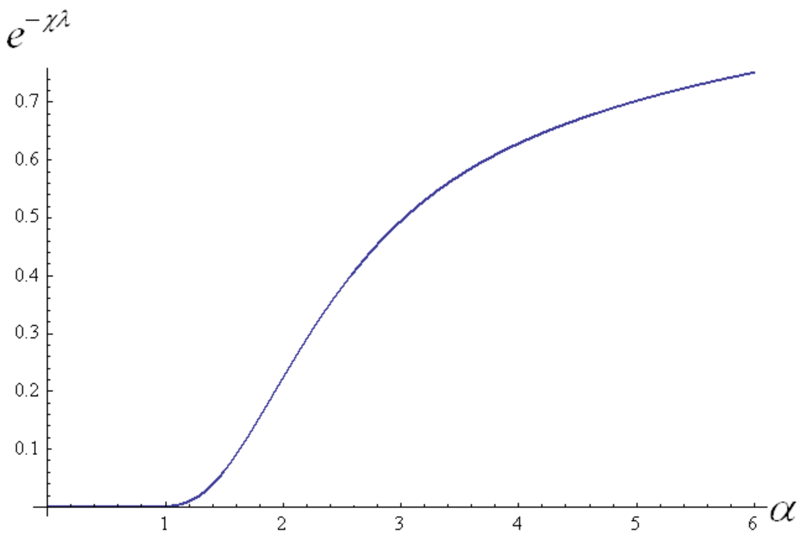


Figure 2.

The change in magnitude inverse of the wavelength obtained relative to the wavelength depends on the oscillation frequency parameter.

Figure 2. illustrates the change in the magnitude of the wavelength relative to the wavelength obtained inversely with the oscillation frequency parameter. As can be seen from the figure, at low values of the oscillation frequency parameter, the extinction of the wave is almost non-existent, while at its large values, the extinction rate of the wave increases significantly.

CONCLUSIONS

Based on the results of the analysis, it was shown that the pulse wave propagation velocity at sufficiently small values of the oscillation frequency parameter is determined by the formula $c_0 = 5\sqrt{\frac{\nu^2}{h^2\gamma^*}}$ -formula, and this formula is called the base pulse wave propagation velocity. It was shown that the propagation velocity of the pulse wave did not differ significantly from the propagation velocity of the base pulse wave at small values of the oscillation frequency parameter. At large values of the oscillation frequency parameter, it was found that the speed of propagation of the pulse wave differs significantly from its base velocity. The extinction of the wave was analyzed depending on the oscillation frequency parameter. The result of the analysis showed that at small values of the oscillation frequency parameter the extinction of the wave almost does not occur, and at its large values the extinction index of the wave increases significantly.

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